Technical Memo

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AN ECONOMETRIC MODEL OF THE JOINT PRODUCTION AND CONSUMPTION OF RESIDENTIAL SPACE HEAT

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by

Yehuda Levi Klein

Energy and Environmental Systems Division

December 1985

work sponsored by

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FOREWORD

In 1979, the U.S. Congress created the Office of Minority Economic Impact (MI) as a component of the U.S. Department of Energy (DOE), out of concern for the effect of energy shortages and rising prices on citizens, particularly those with low incomes, who belong to minority groups. The legislation [42 U.S.C., Sec. 7141 (C)] defines a minority group as one consisting of black, Oriental, American Indian, Eskimo, or Aleut citizens, or Puerto Rican or other Spanish-speaking citizens of Spanish descent. The legislation required MI, among other things, to conduct research to (1) determine the average energy consumption and use patterns of minority groups relative to other population groups and (2) evaluate the percentage of disposable income spent on energy by minority groups relative to other population groups.

As part of its compliance with this mandate, MI commissioned Argonne National Laboratory to conduct a multiyear research program to determine energy consumption and expenditures by minority groups. The Argonne program consists of three tasks:

- Assemble a data base and develop the tools necessary to assess the effects of government energy policies and programs on minority groups;
- Assess the effects on minorities of government programs relevant to those groups and identify options for modifying those programs (e.g., with policy, regulatory, or legislative changes) to alleviate any hardships they may cause for minority groups; and
- Provide market research assistance to energy-related businesses owned by members of minority groups.

This report is one of a series produced by Argonne in the performance of these tasks. The study models the residential demand for space heat, a nonmarket good, and the derived demand for energy and capital as factors in the production of space heat. The modeling framework developed in this study can be used to study the differences in energy consumption patterns across population groups and the impact on poor and minority households of alternative government energy policies. This capability is illustrated in a simulation of the impacts of rising energy prices on poor and nonpoor households. Further information on the overall research program can be obtained by contacting the research officer for the DOE's Office of Minority Economic Impact, Georgia Johnson, or the principal investigator at Argonne, James A. Throgmorton.

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ABSTRACT

This study models the production and consumption of residential space heat, a nonmarket good. Production reflects capital investment decisions of households; consumption reflects final demand decisions given the existing capital stock. In the model, the production relationship is represented by a translog cost equation and an energy factor share equation. Consumption is represented by a log-linear demand equation. This system of three equations -- cost, fuel share, and final demand -- is estimated simultaneously. Results are presented for two cross-sections of households surveyed in 1973 and 1981. Estimates of own-price and cross-price elasticities of factor demand are of the correct sign, and less than one in magnitude. The price elasticity of final demand is about -0.4; the income elasticity of final demand is less than 0.1. Short-run and long-run elasticities of demand for energy are about -0.3 and -0.6, respectively. These results suggest that price-induced decreases in the use of energy for space heat are attributable equally to changes in final demand and to energy conservation, the substitution of capital for energy in the production of space heat. The model is used to simulate the behavior of poor and nonpoor households during a period of rising energy prices. This simulation illustrates the greater impact of rising prices on poor households.

1 RESIDENTIAL PRODUCTION AND CONSUMPTION OF SPACE HEAT

The demand for residential energy arises from the desire for basic amenities, such as heated or cooled living space, hot water, and cooked food. These amenities are nonmarket goods; they are simultaneously produced and consumed within the household. Conceptually, production and consumption are separable: the production decision involves the optimal choice of factor inputs, given the desired amenity; the consumption decision involves the choice of the level of amenity, given the price of that amenity relative to other goods.

This study focuses on residential demand for space heat. This focus was chosen for the following reasons:

1. Space heat accounts for over half the residential energy consumed in a typical household (Newman and Day, 1975). An increase in the price of the primary heating fuel may have a noticeable impact on disposable income, particularly in poor households; and

2. Energy demand for space heat can be controlled in the short run by changing final demand for space heat (i.e., adjusting the thermostat) and in the long run by changing production technology (i.e., substituting capital for energy, conserving energy, and switching fuels).

This study draws on earlier research in residential energy demand and on the household production function literature. This integration of household production theory and consumer demand theory makes a sharp distinction between long-run and short-run behavior. Long-run behavior involves a change in the technology used to produce heat; that is, a shift in the factor shares. Short-run behavior involves a change in final demand. This study draws on a unique data base comprising two household surveys conducted in 1973 and 1981. This data base enables us to estimate impacts on the long-run and short-run behavior of households of the changes in relative fuel prices that took place over that period.

This study is organized as follows: Sec. 1 presents background information on the characteristics of residential energy demand and gives a historical overview of residential energy use. Section 2 surveys past research on residential energy use. Section 3 derives a theoretical model of the residential production and demand for space heat. Section 4 presents empirical methods and data sources. Section 5 discusses empirical results. Section 6 illustrates applications of the model to selected policy questions and suggests directions for future research.

1.1 OVERVIEW OF RESIDENTIAL PATTERNS OF ENERGY CONSUMPTION AND EXPENDITURE

Energy was a matter of little concern to most Americans prior to 1973. The average price of residential energy had, in the case of electricity, been steadily decreasing or, in the case of natural gas and fuel oil, rising only slightly. Then, in 1973, this situation changed dramatically (see Fig. 1.1). Primarily as a result of the oil embargo, prices of fuel oil and other fuels (in constant dollars) began to rise dramatically at first, then more slowly as energy conservation measures and an economic recession reduced the demand for residential energy. Energy prices continued to increase slowly until 1979 when the Shah of Iran was overthrown and the price of imported oil shot upwards once again. As oil prices rose, demand again declined due to the combined effects of prices, governmental programs, and an economic recession. As the demand for crude oil declined, an oversupply of oil began to develop. High prices could no longer be maintained. As the price of oil declined in 1981 and 1982, the incentive to conserve energy also declined.

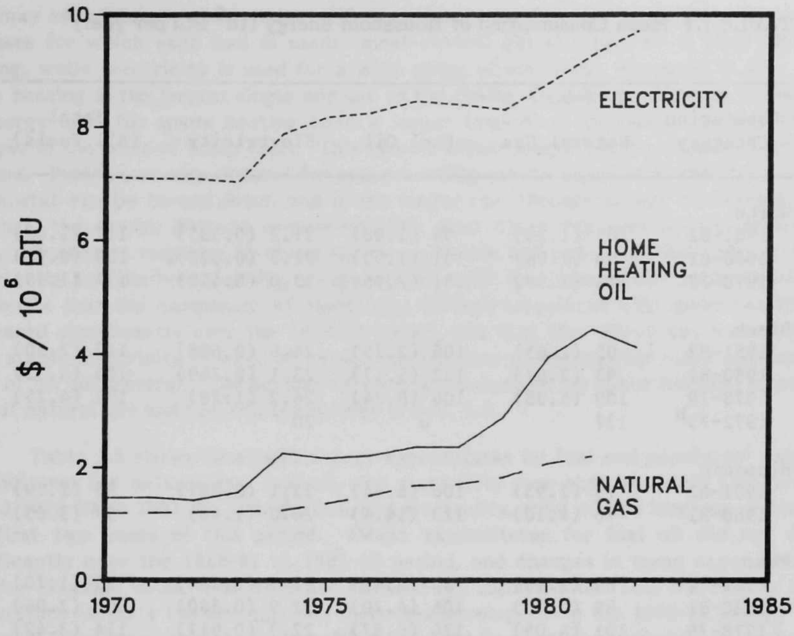

FIGURE 1.1 Energy Prices in the Residential Sector: 1970-82 (constant 1972 dollars)

This section provides an overview of residential patterns of energy consumption and expenditure during this period of rising energy prices. Five sets of data are analyzed:

- The 1973 and 1975 surveys conducted by the Washington Center for Metropolitan Studies (WCMS),
- The 1978-79 National Interim Energy Consumption Survey (NIECS),
- The 1980-81 Residential Energy Consumption Survey (RECS-1), and
- The 1981-82 Residential Energy Consumption Survey (RECS-2).

These data bases were derived from surveys of 1000 to 6000 households, which were drawn from a national multistage probability sample.

Household consumption of natural gas and fuel oil decreased over the 1973-82 period. In contrast, household electricity demand was relatively flat over this period (see Table 1.1). This pattern of change in fuel demand is due, in part, to differences among these fuels in the rate of price change over this period (see Fig. 1.1). A second factor

TABLE 1.1 Mean Consumption of Household Energy (10^6 Btu per year)[a]

Population Category	Natural Gas	Fuel Oil	Electricity	Total (All Fuels)
White				
1981-82	105 (1.29)	94 (1.98)	31.2 (0.335)	111 (1.03)
1980-81	98 (1.08)	101 (1.90)	31.5 (0.328)	109 (0.91)
1978-79	116 (1.59)	131 (2.75)	33.0 (0.459)	134 (1.35)
Black				
1981-82	95 (2.65)	106 (2.75)	24.6 (0.608)	118 (2.50)
1980-81	93 (3.67)	122 (5.17)	23.1 (0.769)	125 (3.32)
1978-79	109 (5.38)	106 (8.24)	26.2 (1.28)	132 (4.75)
1972-73[b]	137	b	20	
Hispanic				
1981-82	75 (2.93)	106 (6.44)	22.1 (0.881)	95 (2.79)
1980-81	76 (4.10)	123 (14.4)	24.0 (1.46)	97 (3.85)
Poor				
1981-82	89 (2.10)	85 (3.42)	22.3 (0.464)	92 (1.70)
1980-81	89 (2.55)	106 (4.70)	22.9 (0.580)	100 (2.06)
1978-79	101 (4.05)	124 (6.87)	22.3 (0.917)	114 (3.42)
1972-73[b]	118	b	17	
Nonpoor				
1981-82	103 (1.28)	98 (2.00)	31.6 (0.340)	115 (1.05)
1980-81	97 (1.11)	104 (1.91)	31.8 (0.336)	112 (0.938)
1978-79	116 (1.63)	129 (2.79)	33.7 (4.69)	136 (1.38)
1972-73[b]	143	b	31	
All				
1981-82	100 (1.10)	96 (1.75)	29.9 (0.288)	111 (0.91)
1980-81	96 (1.02)	105 (1.78)	30.2 (0.298)	110 (0.85)
1978-79	114 (1.52)	129 (2.59)	32.2 (0.431)	134 (1.29)
1972-73[b]	139	b	28	

[a]Numbers in parentheses are standard errors of the mean. Standard errors are not available for 1972-73.

[b]Data on fuel oil consumption are not available for 1972-73.

Sources: NIECS, RECS 1, and RECS 2 public use data tapes. Newman and Day (1975).

that may contribute to the striking difference between electricity and other fuels is the end uses for which each fuel is used: most natural gas and fuel oil is used for space heating, while electricity is used for a wide range of end uses. We noted in Sec. 1 that space heating is the largest single end use in the typical household. Changes in the price of energy used for space heating have a larger impact on disposable income than do changes in the price of other fuels. This income effect magnifies the impact of prices on demand. Further, energy demand for space heating can be adjusted in the short run (the thermostat can be turned down) and in the longer run (through energy conservation). In contrast, the energy demand associated with most other end uses is smaller and less easily adjusted in response to changing energy prices and other factors. Thus both the opportunity and the incentive for energy conservation are greatest for space heating. It is possible that the component of electricity demand associated with space heating also decreased significantly over the 1978-82 period, but that this effect was masked by the more stable electricity demand of households that use electricity for other end uses only (80% of all households). The pattern of electricity demand for space heating, relative to that of natural gas and fuel oil, is explored in Sec. 1.2.

Table 1.2 shows household energy expenditures by fuel and population category. Expenditures for natural gas, fuel oil, and electricity rose approximately 50% over the period 1978-79 to 1981-82. For fuel oil and electricity, most of this increase occurred in the first two years of this period. (Mean expenditures for fuel oil did not change significantly over the 1980-81 to 1981-82 period, and changes in mean expenditures by fuel for Hispanic households were not statistically significant.) This increase in energy expenditure reflects the energy price increases accompanying the 1979-80 energy crisis. The price increase outweighs the resulting decrease in energy consumption over the same period. Total energy expenditures of black and white households are similar. In contrast, poor households (i.e., those with income at or below 125% of the poverty line defined by the U.S. Department of Labor, Bureau of Labor Statistics) spent significantly less on energy than did nonpoor households in each period. Total energy expenditures of white and black households are similar to those of nonpoor households, while expenditure patterns of Hispanic households parallel those of poor households. A comparison with the 1972-73 WCMS survey shows that natural gas and electricity expenditures approximately doubled over the 1972-78 period. This pattern holds for both fuels and all population categories for which data are available.

Table 1.3 presents mean expenditures for household energy as a percentage of household income. The observed long-term trend in the energy expenditure share over the 1972-82 period reflects the impact of the energy price shocks of 1973-74 and 1979-80. For the total population, the energy expenditure share doubled over this period, from 3% to 6% of household income. The long-run trend in energy expenditure shares across population categories shows a similar pattern.

An examination of the trend in energy expenditure shares from 1978 to 1982 shows a marked rise from 1978-79 to 1980-81, followed by a comparable drop over the succeeding period. This finding suggests that the extremely high energy expenditure shares observed in 1980-81 -- 15% for blacks and 23% for poor households -- may reflect the particular circumstances of that period rather than a long-term trend. The severity of the 1980-81 heating season and the impact of the 1979-80 oil crisis on energy prices are possible contributing factors.

TABLE 1.2 Mean Expenditures for Household Energy (current dollars per year)[a]

Population Category	Natural Gas	Fuel Oil	Electricity	Total (All Fuels)
White				
1981-82	471 (5.63)	834 (17.61)	566 (5.34)	878 (10.21)
1980-81	378 (4.19)	815 (15.42)	507 (4.60)	885 (6.76)
1978-79	316 (4.22)	514 (10.98)	396 (4.28)	671 (6.95)
Black				
1981-82	463 (12.00)	955 (40.23)	501 (11.06)	878 (26.96)
1980-81	385 (13.72)	979 (41.41)	414 (11.91)	939 (22.79)
1978-79	306 (16.42)	420 (32.97)	343 (13.45)	598 (26.73)
1972-73	161	b	147	308
Hispanic				
1981-82	342 (14.10)	946 (57.80)	453 (15.42)	735 (30.42)
1980-81	302 (17.72)	991 (117)	411 (20.92)	746 (30.44)
Poor				
1981-82	411 (9.18)	758 (30.28)	426 (7.59)	708 (17.87)
1980-81	353 (9.70)	852 (37.81)	377 (8.13)	770 (14.34)
1978-79	279 (10.74)	486 (27.53)	274 (8.08)	491 (17.38)
1972-73	147	b	131	278
Nonpoor				
1981-82	470 (5.63)	875 (17.84)	581 (5.45)	895 (10.27)
1980-81	378 (4.31)	838 (15.54)	516 (4.72)	907 (6.98)
1978-79	319 (4.42)	507 (11.14)	407 (4.41)	683 (7.10)
1972-73	168	b	201	369
All				
1981-82	459 (4.84)	856 (15.55)	552 (4.63)	866 (9.11)
1980-81	374 (3.95)	841 (14.40)	491 (4.20)	882 (6.32)
1978-79	314 (4.10)	504 (10.35)	390 (4.05)	662 (6.70)
1972-73	164	b	188	352

[a]Numbers in parentheses are standard errors of the mean. Standard errors are not available for 1972-73.

[b]Data for fuel oil consumption are not available for 1972-73.

Sources: NIECS, RECS 1, and RECS 2 public use data tapes. Newman and Day (1975).

TABLE 1.3 Household Expenditure on Electricity, Natural Gas, and Fuel Oil as a Share of Income[a]

Population Category	Energy Outlays ($)	Income[b] ($)	Energy Outlays as % of Income
White			
1981-82	878 (10.21)	22,000 (240)	6.1 (0.16)
1980-81	885 (6.76)	20,000 (210)	7.4 (0.13)
1978-79	671 (6.95)	17,000 (210)	5.7 (0.13)
Black			
1981-82	878 (26.96)	13,000 (410)	9.6 (0.52)
1980-81	939 (22.79)	12,000 (500)	15.1 (0.78)
1978-79	598 (26.37)	11,000 (420)	9.3 (0.74)
1972-73	308	7,500	4.1
Hispanic			
1981-82	735 (30.42)	18,000 (650)	6.5 (0.64)
1980-81	746 (30.44)	16,000 (930)	9.1 (1.0)
Poor			
1981-82	708 (17.87)	4,700 (67)	18 (0.66)
1980-81	770 (14.34)	4,400 (76)	23 (0.59)
1978-79	491 (17.38)	3,300 (96)	19 (0.85)
1972-73	278	2,500	11
Nonpoor			
1981-82	895 (10.27)	25,000 (230)	4.3 (0.07)
1980-81	907 (6.98)	23,000 (210)	5.2 (0.06)
1978-79	683 (7.10)	19,000 (200)	4.4 (0.06)
1972-73	369	14,000	2.6
All			
1981-82	866 (9.11)	21,000 (210)	6.4 (0.15)
1980-81	882 (6.32)	19,000 (190)	8.3 (0.14)
1978-79	662 (6.70)	17,000 (200)	6.0 (0.13)
1972-73	352	12,000	2.9

[a]Numbers in parentheses are standard errors of the mean. Standard errors are not available for 1972-73.

[b]Income data are for the year prior to the survey (1980 for RECS 2, 1979 for RECS 1, 1977 for NIECS).

Sources: NIECS, RECS 1, and RECS 2 public use data tapes. Newman and Day (1975).

The energy expenditure shares observed for black and poor households in the 1978-82 period are quite high, especially when compared to shares in the 1972-73 pre-embargo period. However, a number of governmental programs have been initiated to mitigate the impact on poor households of increasing energy prices and energy expenditures as a share of income. These include the federal Low Income Home Energy Assistance (LIHEAP) and weatherization programs, and programs initiated by state regulatory commissions. Perhaps the most important federal program with this objective is LIHEAP. LIHEAP is targeted toward poor households that need assistance in paying home heating bills. LIHEAP reaches approximately 15% of households that meet national eligibility criteria, and subsidizes, on average, 41% of the recipient household's space heating costs. (See U.S. Department of Health and Human Services, 1983, p. 21.) The impact of LIHEAP on the energy expenditures and expenditure shares of LIHEAP recipients is shown in Table 1.4.* LIHEAP recipients spend nearly 15% more on energy than households that are eligible for, but do not receive, LIHEAP assistance. The energy expenditure share of LIHEAP recipients is correspondingly higher than that of eligible nonrecipients. The most likely explanation for this effect is that LIHEAP assistance enables recipients to support basic energy services, particularly space heating.

In this section we present data on the variation in residential energy consumption, expenditures, and expenditures as a share of income across groups over the

TABLE 1.4 Household Expenditure as a Share of Income: Impact of the Low Income Home Energy Assistance Program (1981-82)[a]

LIHEAP Eligibility	Energy Outlays ($)	Income ($)	Energy Outlays as % of Income
Not eligible	909 (11.37)	27,000 (260)	4 (0.1)
Eligible, Nonrecipient	731 (15.17)	8,000 (160)	13 (0.1)
Recipient	832 (38.21)[b]	7,000 (330)[b]	19 (1.0)[b]

[a]Numbers in parentheses are standard errors of the mean.

[b]Data are significantly different from data for "eligible, nonrecipient" households.

Source: RECS-2 public use data tape.

*Data are presented for 1981-82, the only period for which information is available. The sample of LIHEAP recipients is too small to permit statistically meaningful comparisons across population categories.

period from 1972-73 through 1981-82. Energy consumption by all groups generally declined over this period, while energy expenditures and expenditures as a share of income generally increased. Reductions in consumption from 1978-79 to 1981-82 were significantly greater for white than for black households. Exceptions to this general pattern were observed, however. Changes in electricity demand were statistically insignificant, natural gas consumption increased for all groups except Hispanics from 1980-81 to 1981-82, and consumption of fuel oil by black households changed erratically from 1978-79 through 1981-82. Further, although expenditures as a share of income increased over the 10-year period, the shares decreased for all groups from 1980-81 to 1981-82.

Recipients of assistance from LIHEAP, a federal program of direct grants for household energy, spent less on energy in 1981-82 than did ineligible households, but more than households that were eligible but did not participate in the program. Recipients spent greater fractions of their income on residential energy than either ineligible or eligible but nonparticipating households.

1.2 PATTERNS OF HOUSEHOLD ENERGY CONSUMPTION AND EXPENDITURE BY END USE

Section 1.1 identifies a general tendency toward decreasing energy demand over time that reflects, in part, price-induced and income-constrained energy conservation. This section examines the patterns of household energy consumption and expenditure for space heating. First, estimates of energy use for space heating are derived from an analysis of the seasonal patterns of fuel use. Using this measure of end-use energy demand, we then characterize the patterns of energy consumption and expenditure for space heat (Anderson, 1984). [An alternative approach to estimate energy demand by end use is discussed in George (1982) and Dubin and McFadden (1984). See Sec. 2.2 for a further discussion of these issues.]

To derive residential energy demand by end use, each household's total fuel demand is split into two (or three) components: space heating, space cooling (for electricity), and base, or non-weather-sensitive, demand. The underlying assumption is that weather-sensitive components of energy demand can be attributed to space heating or space cooling requirements. In fact, energy use for lighting and appliances also has a seasonal component. However, in the absence of direct metering of end-use loads, this approach should provide a reasonable proxy for fuel demand for space heat. Seasonal components of fuel use for each household are derived as follows:

- The lowest three months of fuel use (for a given fuel) are defined as the base load.

- The year is divided into a heating season and a cooling season on the basis of monthly data on heating degree-days and cooling degree-days.

- For each billing period or delivery period that falls within the heating season, fuel demand in excess of the average base load is interpreted as heating demand.

The derivation of space heating demand for a typical household from monthly billing data is shown in Fig. 1.2.

Table 1.5 presents mean energy consumption for space heating for those households using natural gas, fuel oil, and electricity as the primary heating fuel. The largest proportional decreases in energy consumption for space heating, averaging 40% over the 1978-82 period, occur in households using electricity as the primary space heating fuel. The average decrease in energy use for space heating for households heating with fuel oil is just under 30%; for households heating with natural gas, it is just over 15%. This contrasts with the results presented in Table 1.1. Total electricity demand, as contrasted with electricity demand for space heating, edged down about 7% over this same period. Total demand for fuel oil decreased about 30%, and total demand for natural gas decreased just over 10%. This pattern reflects the share of each fuel used for space heating. For example, electricity is used for a broad range of end uses by nearly all households; it is used for space heating by only 20% of all households.

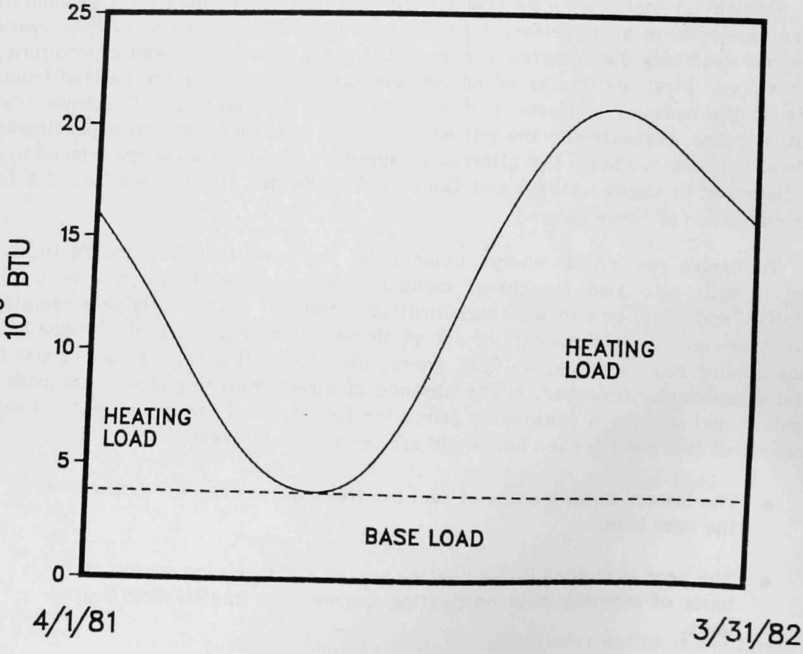

FIGURE 1.2 Derivation of Space Heating Energy Demand from Monthly Billing Data

TABLE 1.5 Mean Household Consumption of Energy for Space Heating (10^6 Btu/yr)[a]

Population Category	Primary Space-Heating Fuel: Natural Gas	Fuel Oil	Electricity
White			
1981-82	85 (1.25)	93 (2.70)	18.8 (0.68)
1978-79	101 (1.47)	123 (3.56)	31.7 (2.20)
Black			
1981-82	91 (3.33)	120 (17.99)	20.3 (1.93)
1978-79	99 (5.47)	125 (13.65)	24.0 (3.35)
Hispanic			
1981-82	59 (3.62)	65 (9.12)	7.84 (1.84)
Poor			
1981-82	81 (2.70)	97 (6.06)	14.65 (1.17)
1978-79	89 (3.80)	130 (14.3)	30.08 (3.43)
Nonpoor			
1981-82	84 (1.24)	94 (2.98)	19.22 (0.71)
1978-79	102 (1.51)	122 (3.56)	31.46 (1.10)
All			
1981-82	84 (1.13)	94 (2.73)	18.44 (0.62)
1978-79	101 (1.41)	123 (3.45)	31.34 (1.04)

Source: NIECS and RECS-2 public use data tapes.

Electricity use for space heating is likely to be more price-sensitive than that for other end uses, for at least two reasons. First, information on the energy efficiency of buildings and furnaces is more readily available than is comparable information concerning other appliances. Second, the energy efficiency of existing buildings and furnaces can be readily upgraded through energy-conserving retrofits and even routine maintenance. The household is thus more likely to be aware of the possibility for capital-energy substitution in the production of space heat than for other end uses. The modest decrease in total electricity demand suggests that electricity demand for non-space-heating end uses is masking this trend in space heating demand. In contrast, fuel oil is used primarily for space heating, and, to a lesser extent, for hot water heating. It follows that the trend of total demand for fuel oil (Table 1.1) parallels fuel oil demand for space heating. Natural gas has several end uses in addition to space heating, and electricity has a wide range of end uses. The decreases in natural gas and electricity demand for space heating are thus proportionately greater than decreases in total demand.

2 REVIEW OF STUDIES OF RESIDENTIAL ENERGY DEMAND

2.1 MODELING LONG-RUN AND SHORT-RUN BEHAVIOR WITH AGGREGATE DATA BASES

Econometric literature on residential energy traditionally uses several approaches to identify long- and short-run demand elasticities (with respect to own price and income). Long run and short run are distinguished as follows: in the long run, capital stock can be adjusted to reflect the changing economic environment; in the short run, the rate of utilization of a fixed capital stock is the only choice variable. It is difficult to directly represent long- and short-run behavior with data aggregated over cities or states, primarily because there are no reliable data on the existing stocks of energy-using capital equipment. Without such data, it is not possible to identify the fraction of the variation in energy use (over time or across households or communities) that is related to short-run variation in utilization rates versus long-run adjustments to capital stock portfolios. Given this data limitation, the studies reviewed here use two basic approaches to separate long-run and short-run behavioral responses. These have been characterized by Taylor (1975) as interpretive versus logical distinctions between long- and short-run demand. In the former approach, a static demand model estimated with cross-section data is interpreted as long run. This interpretation is problematic unless the data for each state represent demand associated with a long-run equilibrium portfolio of energy-using capital stock. It is more likely that various communities will be in disequilibria, capital stocks having been only partially adjusted to reflect previous price changes. Therefore these data will reflect significant short- as well as long-run effects.

A logical distinction between short- and long-run demand is made by estimating an explicitly dynamic model on time series or pooled cross-section/time-series (CS-TS) data. Dynamic models, which are discussed below, include adaptive expectations, partial lagged adjustment, and "habit" models. These dynamic models measure, at best, a proxy for the behavior of interest. For example, in a dynamic "habit formation" model, the current period demand is regressed on the previous period's demand (as well as on a set of other explanatory variables). Previous-period consumption is a proxy for the stock of both physical capital and habitual patterns of appliance use. Such models, in the absence of appliance stock data, cannot distinguish constraints on short-run demand adjustment imposed by existing appliance portfolios from constraints imposed by habit.

Similarly, adaptive expectations or partial adjustment models explicitly distinguish short-run and long-run demand in terms of the stock of energy-using durable goods:

- Short-run demand for energy is based on the utilization of a fixed portfolio of appliances.

- Long-run demand is based on the rate of growth of that portfolio.

Fisher and Kaysen (1962) estimate a model of electricity demand. However, due primarily to the limitations of aggregate data on appliance stocks, Fisher and Kaysen were not able to estimate an integrated model of demand in the long and short run. Rather, two separate models were estimated. The long-run demand model estimates the growth of appliances as a function of permanent income and of prices for electric and gas appliances and fuel. The poor quality of the appliance stock data may explain the generally weak and, in some instances, counterintuitive results (e.g., negative long-run income elasticities, insignificant price elasticities).

The short-run demand model is based on the following key relationships:

$$D_t = \sum_i K_{it} W_{it} \tag{2.1}$$

where:

D_t = energy consumption in period t,

W_{it} = average stock of appliance type i in period t, and

K_{it} = average utilization rate of appliance type i in period t,

and

$$K_{it} = \alpha P_t^{\beta} Y_t^{\gamma} \tag{2.2}$$

where:

P_t = energy price,

Y_t = income, and

α, β, γ = coefficients.

The first relationship (Eq. 2.1) specifies demand as a function of appliance stock (fixed in the short run) and appliance utilization rate. The second (Eq. 2.2) specifies utilization rate as a function of energy price and income. Given the ambiguous nature of the stock variable W_{it} (measured in units of annual energy consumed at an average utilization rate), Fisher and Kaysen do not estimate this model directly. The stock term is eliminated as follows:

- By assumption, W_{it} grows exponentially over time.
- The form in which short-run demand is estimated is a first differences model.

The equation to be estimated is hence:

$$\begin{aligned}\left(\ln D_t - \ln D_{t-1}\right) = \alpha &+ \beta\left(\ln P_t - \ln P_{t-1}\right) \\ &+ \gamma\left(\ln Y_t - \ln Y_{t-1}\right)\end{aligned} \tag{2.3}$$

The coefficients β and γ capture period-to-period (short-run) determinants of demand. The constant term is interpreted as a proxy for the exponential growth of appliance stock.

A key difficulty posed by Fisher and Kaysen's effort to specify models for electricity demand in the short and long run is the incompatibility of the two models. The long-term model measures the stock of energy-using appliances (W_{it}) in physical units and estimates the long-term growth of appliance stocks in terms of underlying economic and demographic variables. In the short-run model, the long-term growth of appliance stocks is approximated by an exponential growth curve. This assumption enables Fisher and Kaysen to estimate a short-run model into which a stock term does not enter; however, it makes it more difficult to interpret the results of the short-run model as reflecting short-run, capital stock constrained behavior.

Houthakker, Verleger, and Sheehan (1974), using a flow adjustment model similar to that of Houthakker and Taylor (1970), jointly estimate the demand for gasoline and residential electricity in the short run and long run. Short-run demand is represented by a two-equation model:

$$q^* = f(p,y) = \alpha \ P^{\beta} \ Y^{\gamma} \tag{2.4}$$

$$q_t/q_{t-1} = \left(q_t^*/q_{t-1}\right)^{\sigma} \tag{2.5}$$

where:

q^* = desired (long-run) demand,

q = actual (short-run) demand, and

σ = rate of adjustment.

Equation 2.4 is a model of "desired" or long-run demand. Equation 2.5 represents the rate at which demand in the short run adjusts to the long-run optimum. This model captures effects of both capital stock holdings and habit on energy use.

Substituting Eq. 2.4 into Eq. 2.5 and putting Eq. 2.5 in log-log form:

$$\ln q_t = \sigma \ln \alpha + \sigma\beta \ln P^{\cdot} + \sigma\gamma \ln Y + (1 - \sigma) \ln q_{t-1} \tag{2.6}$$

The coefficients of the estimated equation $\sigma\beta$ and $\sigma\gamma$ can be interpreted as short-run demand elasticities. The coefficient $(1 - \sigma)$ of the lagged dependent variable $\ln q_{t-1}$ can be used to recover the long-run elasticities β and γ.

Houthakker, Verleger, and Sheehan estimated this model on a pooled CS-TS sample of annual observations of state aggregates for the period 1960-71, and on a set of TS observations for each state. One result of note is the estimated coefficient of the lagged dependent variable $(1 - \sigma)$, which is over 0.9. This result suggests that the short-run energy demand is substantially influenced by some combination of existing capital stocks and habitual patterns of appliance usage.

Halvorsen (1978) discusses alternative static and dynamic model specifications for residential electricity demand in the long and short run. The long-run demand is first estimated in a static model with 48-state cross-section data for the years 1961-69 (nine separate CS samples). The set of explanatory variables includes, in addition to income and electricity price, the price of utility gas, an electric appliance index, and weather and demographic variables. The dynamic versions of the model also incorporate various simple and distributed lags on the explanatory variables. In general, the results seem reasonable. Estimated long-run price elasticities are greater than one; income elasticities are large but less than one. Elasticities of demand with respect to the price of natural gas are very small. Moreover, the coefficient of the electric appliance price index is not significant. Since, in the long run, fuel switching (changing, for example, from a gas to an electric stove) should have a significant impact on demand for electricity, it is at least surprising that neither appliance nor natural gas prices have an important impact on long-run demand.

The short-run model is estimated against aggregate TS data for 1961-75, with an estimation performed for each state separately as well as for a national sample. Halvorsen explored alternative model specifications, using distributed lags on price and income variables and, alternatively, distributed lags on the dependent variable. He notes that the former can be interpreted as a partial adjustment or adaptive expectations model; the latter, a habit formation model. Insisting that there is no prior basis for comparing the two specifications, Halvorsen opts for the better fit: a model incorporating lagged independent variables. Such a model can be interpreted as a partial adjustment or an adaptive expectations model.

Bohi (1981) notes that the lag specifications used by Houthakker and Taylor (1970) and, earlier, by Koyck (1954) are "simple and convenient," do not require data on capital stocks, and capture the lagged effects of price changes with just two parameter estimates. Bohi points out, however, that the class of lagged adjustment models is not well grounded in economic theory. The form of the lagged adjustment models implies that the largest response to a price change occurs in the first period, and that the adjustments decline geometrically in each succeeding period. There is no reason to expect the behavioral response to a price change to follow this pattern.

As this selective review of the econometric literature indicates, it is difficult to construct demand models that can be (1) interpreted in terms of the interrelationship between capital stock and energy demand and (2) estimated using aggregate data sets (such as census or other statewide data). The alternative approach of specifying econometric models that can be interpreted as long or short run is not an adequate substitute for a model in which the effects of appliance holdings are directly represented.

2.2 MODELING LONG-RUN AND SHORT-RUN ENERGY DEMAND BEHAVIOR WITH HOUSEHOLD SURVEY DATA

The use of household survey data simplifies the task of differentiating long-run and short-run behavior. Several household surveys of appliance holdings and energy use have recently become available. These surveys make it possible to estimate residential energy demand models with disaggregate data. The first national surveys were conducted in 1973 and 1975 by the Washington Center for Metropolitan Studies (WCMS) and the Federal Energy Administration (now the Energy Information Administration of the U.S. Department of Energy, DOE-EIA). Surveying a total of over 3000 households, the WCMS study obtained detailed information on demographic characteristics (e.g., household income, year of moving into residence), residence characteristics (e.g., thermal attributes, size, roof type), heating system characteristics (e.g., fuel used, furnace type, supplemental heating system type), and energy price data. (See Nicoletti, 1977, for a detailed description of the WCMS data base.)

The Midwest Research Institute (MRI) conducted a random household appliance survey in 1976 under the auspices of the Electric Power Research Institute (EPRI) and the Federal Energy Administration (FEA). This survey was a stratified sample of 2000 households drawn from 16 cities. The data base includes demographic information, appliance ownership data, and electricity rate data. The survey also includes crude information on the thermal characteristics of the housing stock, from which a rough index of thermal load could be calculated. (See Harper et al., 1979, for a detailed description of the MRI survey.) The DOE-EIA, beginning in 1978, has conducted annual Residential Energy Consumption Surveys (RECS). These surveys, each comprising 4000-6000 households drawn from a national, multistage probability sample, are the best source of information on trends in residential energy demand at the household level.

The availability of household survey data makes it possible to directly incorporate information on capital stocks into energy demand models. One approach is to estimate the energy demand for each end use, conditional on the stock of energy-using capital equipment. This method, conditional demand estimation, expresses total household demand as the sum of demands for each end use. It permits one to identify the influence of a price or income change on the energy demand for each appliance, and, by construction, for total household demand. These responses are short run in nature; they reflect changes in the rate of utilization of a given capital stock. Conditional demand estimation is not an appropriate technique for estimating long-run effects; it does not estimate the factors that determine the decision to use a given appliance.

With the conditional demand method, total demand is regressed on many dummy variables and interaction terms of dummy variables with other explanatory variables. For example, a model of electricity demand might use three dummy variables -- space heat, air conditioning, and hot water -- each taking on a value of "1" if electricity is used for that end use and "0" if not. Income may be introduced in four terms, once alone, and then interacted with each dummy variable. These terms represent the effect of income on electricity demand for space heat, air conditioning, hot water, and all other end uses. This process is followed, as appropriate, with other explanatory variables such as energy prices, weather variables, and demographic variables. With the estimated coefficients for a conditional energy demand model and information on the appliance holdings and other characteristics of a given household, each end-use demand can then be estimated. Population estimates of end-use demand can then be derived from these estimates for each household. Parti and Parti (1980) estimate the electricity demand for each of 16 appliances, using survey data for 5000 households in San Diego County, California. They report results from 12 consecutive monthly cross-section regression analyses. In general, annual estimates of air conditioning and space heating loads are lower than corresponding engineering estimates of typical energy requirements for those end uses. In contrast, estimated hot water loads are higher than engineering estimates of energy requirements. Average estimated energy loads for other appliances fall within the range predicted by engineering studies of electricity requirements.

The price and income coefficients in the conditional demand model represent the appliance-specific short-run demand elasticities. Parti and Parti derive population estimates of the short-run demand elasticities, across all end uses, by summing the appliance-specific elasticities, which are weighted by the fraction of households that uses a given appliance. Their estimates of short-run price and income elasticities of demand are -0.58 and 0.15 respectively. The price elasticity is above the range of estimates obtained by other electricity demand studies, although the income elasticity is within the range of other studies. (See Bohi, 1981, Table 3.1.) A similar conditional demand model has been estimated by George (1982). This approach has been used by Barnes, Gillingham, and Hagemann (1982) to study the residential demand for natural gas, and by Aigner, Sorooshian, and Kerwin (1984) to study residential end-use load profiles, that is, patterns of appliance usage by time of day.

Dubin and McFadden (1984) suggest that this approach of estimating energy demand for each end use by least squares decomposition of total demand has the potential for severe bias. Economic theory suggests that the demand for an energy-using durable good is related to the chosen rate of use. For example, a household preference for maintaining an inside temperature of 68°F throughout the summer will affect both the choice of air conditioning system and the intensity with which that system is used. This unobserved preference introduces a bias in the conditional demand model because the preference, which is picked up in the error term, is correlated with an explanatory variable (the appliance dummy variable). Similar biases are introduced in estimates of price and income elasticities. Dubin and McFadden recommend dealing with the endogeneity of appliance choice (the correlation between appliance choice and use decisions) by explicitly modeling the two separate decisions: (1) appliance choice and (2) energy use conditioned upon appliance choice. The approach followed by Dubin and McFadden is to model appliance choice and use in a joint discrete/continuous choice framework (see Sec. 2.3). Appliance choice is represented by a discrete choice model (e.g., logit); energy demand is conditioned on appliance holdings.

A simpler approach is to estimate (1) an appliance stock equation and (2) energy demand for a given appliance stock. This approach is followed by Garbacz (1983). Garbacz estimates a three-equation model: electricity demand, electricity price, and the stock of electricity-using appliances. The appliance stock equation represents the appliance stock index as a function of income, the price of electricity, weather, and demographic variables. (The price of capital is not included in the appliance stock equation.) The demand equation represents electricity use as a function of price, income, the endogenous appliance stock index, and weather. The electricity price equation estimates the marginal cost of electricity as a function of quantity consumed and several locational dummy variables. This equation is a simplified representation of the declining-block structure of electricity rates.

The dependent variable in the appliance stock equation is an index of electricity-using appliances, measured in terms of annual energy use (millions of Btus per year). Each appliance is assigned a value on the basis of typical annual energy consumption; the value of the appliance stock index reflects the expected annual electricity consumption for a household using a given set of appliances. This specification of appliance stock was selected as an alternative to the use of one or several endogenous discrete variables to represent appliance choice (see Sec. 2.3).

Garbacz cites two advantages of the appliance index specification, in contrast to the discrete choice specification: (1) the index weights each appliance by typical intensity of use, and (2) the estimation procedure is simplified by the use of a continuous dependent variable. However, the appliance index specification gives a common weight to each appliance. It thus implies that the relative pattern of use of two given appliances is constant across all households that use both appliances. Consider a 10% increase in income that induces household A to increase the rate of use of an existing air conditioner, and household B to install a new air conditioner. The appliance index specification would imply that, other things being equal, both households would use the same stock in the same way. As noted above, it is likely that the same unobserved household characteristics that influence appliance choice will affect the rate of appliance use. In this instance, the factors that would cause household A to adopt air conditioning before household B should also cause it to use that system more intensively.

The price and income coefficients in the demand equation represent short-run (or direct) demand elasticities. Long-run (or total) elasticities reflect the indirect effect of prices and income on demand, by inducing a change in the appliance stock. Garbacz estimates direct and total price elasticities of demand for electricity of -0.19 and -1.40, respectively, and direct and total income elasticities of 0.10 and 0.41, respectively. The estimated short-run elasticities and the long-run income elasticity are comparable to those obtained by other researchers using household survey data; the long-run price elasticity is higher than that obtained by other studies using similar data (see Bohi, 1981, Table 3.1).

2.3 DISCRETE CHOICE MODELS OF APPLIANCE CHOICE AND USE

The discrete choice models discussed in this section are applications of the basic approach of McFadden (1973). A discrete choice model is derived from a representation of an individual's choice environment, characterized by $<s>$; a vector of attributes of the individual in question; and a vector of attributes x_j characterizing each of J alternatives available to him (indexed j = 1, ..., J). Let U, the individual's indirect utility function, be defined as:

$$U = V_{s,x} + u_{s,x} \tag{2.7}$$

where:

V, nonstochastic, reflects the representative tastes of the population; and

u, stochastic, reflects individual differences in preferences.

To simplify notation, the argument "s" is suppressed. The probability that an individual chosen at random from the population will choose alternative i is thus:

$$Pr(i) = Pr[u(x_j) - u(x_i) < V(x_i) - V(x_j), \text{ for all } j] \tag{2.8}$$

If a suitable family of cumulative distribution functions is specified for the vector of error terms u(x), and if a functional form is given for the strict utility function V(x), then econometrically testable choice models can be specified. Thus, for example, if u is assumed to be independently, identically distributed with the extreme value distribution, $P[u(x_i) < u] = \exp(-\exp\ -u)$, then the multinomial logit model is generated. Alternatively, if u is assumed identically, independently distributed normal, the multinomial probit model is generated. These two distributions have found the widest range of economic applications. The extreme value distribution is similar in shape to the normal distribution, although positively skewed (see McFadden, 1973). The principal advantage of the multinomial logit model lies in its computational tractability; it has a closed-form solution, and a number of efficient computer programs have been developed to calculate estimates (McFadden, 1976). Multinomial probit, on the other hand, has no closed-form solution and is computationally infeasible for as few as five or six alternatives.

The choice probabilities associated with the multinomial logit model are:

$$Pr(i) = \exp\ [V(x_i)] \Big/ \textstyle\sum_j \exp\ [V(x_j)] \tag{2.9}$$

The following applications of discrete choice modeling to energy-consumption-related decisions rely on the multinomial logit or closely related models.

Baughman and Joskow (1975) use a binomial logit model to estimate the fuel choices for residential space heating, water heating, and cooking. The strict utility function is specified as linear in parameters:

$$V_j = \beta_0 + \beta_1 K_j + \beta_2 P_j + \beta_3 X \tag{2.10}$$

where:

K_j = capital cost of alternative j,

P_j = effective fuel cost (adjusted for conversion efficiency),

X = vector of other characteristics (e.g., convenience), and

β = coefficients.

The relative probability of two alternatives i and j being chosen is:

$$\log[Pr(i)/Pr(j)] = V_i/V_j \tag{2.11}$$

Baughman and Joskow use frequency data taken from a cross-section of 48 states for the year 1969 to estimate the log-odds model represented in Eq. 2.11. (They found little variation in the cost of energy-using capital goods. Effects of relative capital costs are captured by the constant term in the regression.) The results indicate that fuel choice, in the long run, is highly price-elastic. For example, a 10% increase in the price of electricity leads to a 21% decrease in the saturation of electric space heating (evaluated at the sample mean). This result suggests that fuel switching as well as fuel savings must be taken into account in evaluating the impacts of government policy.

Lin, Hirst, and Cohn (1976) specify a conditional logit model of appliance fuel choice quite similar to that of Baughman and Joskow (1975), discussed above. A multinomial log-odds model, log Pr(i)/[1 - Pr(i)], is estimated against 1970 frequency data for 48 states. The model is less restrictive in that the cross-price elasticities of each alternative j with respect to the price of fuel i are not constrained to be equal. Like Baughman and Joskow, Lin, Hirst, and Cohn find little variation in relative capital costs for space heating. Capital cost variables for cooking, however, give reasonable results. Saturation elasticities are similar to those found by Baughman and Joskow (1975); own-price saturation elasticities are greater than one, and cross-price elasticities are generally of the correct sign. Additionally, equipment price saturation elasticities are estimated, with similar results.

Due to limited data, Baughman and Joskow (1975) and Lin, Hirst, and Cohn (1976) were forced to rely upon aggregated data sources. Analysis carried out at the state level however, loses substantial intrastate price and weather variation is lost. More important than this loss of detail is the instability of such analysis data is unable to measure the effects of important explanatory variables. Individual differences in household thermal characteristics (rate of heat loss) and demographic characteristics (i.e., income) affect the costs and choices of each household; these variables can only be captured in household survey data. Finally, the cited studies have been based, by necessity, on data collected at one point, or at most on two decennial censuses. With such data, it is impossible to evaluate the response of appliance holdings to short-run variations in economic conditions.

Several studies use energy consumption data drawn from national household surveys for the calibration of disaggregate models of discrete choice. Hausman (1979) specifies a random utility model of appliance choice from which he derives an econometric model of air conditioner choice. The models assume that the consumer faces a two-commodity world, air cooling and a market basket of other goods. Air cooling, the service provided by an air conditioner, is assumed to be independent of the particular model of air conditioner chosen. Also, (in the long-run choice model) the quantity of cooling demanded is assumed invariant under the choice of air conditioner model. (The short-run optimization of thermostat setting as a function of the operating costs of the air conditioner chosen is represented in a parallel model of short-run behavioral choice.) In the long run, the only determinants of appliance choice are initial (capital) cost and operating costs over time. The indirect utility function is thus of the form:

$$W = V(K, p, Y, \pi) \tag{2.12}$$

where:

K = capital cost of a given appliance alternative,

p = associated vector of operating costs (the time subscript is suppressed), and

π = general price index of other consumption goods.

An econometric model of discrete choice, derived from this model of individual utility, is calibrated against the MRI data base. (See the beginning of this section for a derivation of a similar discrete choice model from the behavior of a utility-maximizing individual.) The key element in this formulation is the tradeoff between capital expenditures and operating (primarily energy) costs; this tradeoff reflects the individual's expectations of future income and operating costs and his subjective rate of time preference.

The most significant contribution of Hausman (1979) is his interpretation of the tradeoff between capital cost and operating cost that underlies appliance choice. The conceptual difficulty lies in separating the effects of time discounting, price expectations, and durability. An imputed high discount rate may reflect an underestimate of either the appliance's lifetime or the future real growth rate of the price of electricity. Only one of these three parameters can be estimated directly; Hausman estimates the subjective rate of time discount given plausible values for the other two parameters. He finds a discount rate of approximately 15% (evaluated at the median income level), close to the market rate for short-term consumer loans. This subjective discount rate varies with household income. It ranges up to 30% and more for income classes below \$8,000 and down to under 10% for income classes above \$35,000. The use of much lower discount rates in the engineering-economic studies discussed in Sec. 2 introduces a bias in favor of capital-intensive (as opposed to energy-intensive) alternatives. Therefore, the "optimal" saturations of energy-efficient appliances and energy-conserving equipment are higher than those resulting from consumer preferences alone.

McFadden, Puig, and Kirshner (1978) estimate the choice of appliance portfolio and electricity consumption conditioned on that portfolio. Their data base is the WCMS 1975 survey of 3249 households. A model of fuel choice for water heat and space heat is estimated for four alternative portfolios, all combinations of electricity- and natural-gas-fueled water and space heat. Although the level of analysis is the single household, relative energy prices were unavailable at that level. Therefore the relative energy price variable is defined as the ratio of electricity cost to average gas cost; costs are statewide average costs to residential customers. Thus intrastate variation in relative energy costs arising from the variability of energy rates and household thermal characteristics is excluded. Notwithstanding these difficulties in obtaining capital and energy cost data, the results of the multinomial logit estimation of water and space heat are fairly good: 72.2% of the choices are predicted correctly and the standard errors of the estimated coefficients are relatively low. Saturation elasticities with respect to relative energy costs are generally high and consistent with the results of Baughman and Joskow (1975) and Lin, Hirst, and Cohn (1976) cited above.

Brownstone (1978) proposes a study of air conditioner choice and of utilization rate conditioned on that choice. He generalizes the Hausman (1979) model by allowing the alternative of not buying an air conditioner. Dubin and McFadden (1984) model the choice of fuel for space heating and water heating together with the demand for electricity, conditioned on fuel choice. The choice and demand models are derived from the indirect utility function. The derivation of the choice model is discussed above (see McFadden, 1973). The demand equations for electricity and an alternative fuel are derived from the indirect conditional utility function using Roy's identity (see also Brownstone, 1978; Hausman, 1979; and Deaton and Muellbauer, 1980.) The short-run own-price, cross-price, and income elasticities of electricity demand are derived from the conditional demand equations. Dubin and McFadden estimate the following short-run elasticities: own-price, -0.2; cross-price, -0.02; and income, 0.20. The long-run elasticities incorporate the effect of a shift in fuel choice on the demand for electricity. The own-price and income elasticities are roughly equal to their corresponding short-run elasticities. In contrast, the long-run cross-price elasticity is approximately 0.4, suggesting that the choice of electric appliances is quite sensitive to the price of competing fuels.

2.4 DEMAND FOR ENERGY AS A FACTOR OF PRODUCTION

Household production theory has been applied to several recent studies that relate the production of household services to the demand for land, capital, energy, and labor. Neels (1981a) specifies a general model of housing services production:

$$Q_h = \beta_0 + \sum_i \beta_i F_i + \sum_i \sum_j \beta_{ij} F_i F_j \tag{2.13}$$

where:

Q_h = quantity of housing produced, in dollars, derived from the monthly rent.

F_i = i^{th} input (land, capital, energy, labor). Land and capital are derived from the total property value and are measured in dollars. Energy, derived from utility bills, is measured in Btus, adjusted for differences among fuels in conversion efficiency. Labor is measured in dollars of expenditure.

β = coefficients.

Input and output variables are in natural log form.

This translog production function can be regarded as a second-order Taylor-series approximation to an arbitrary twice-differentiable production function. Neels tests this flexible specification against alternative, more-restrictive models. He considers restrictions on the functional form of the production function (Cobb-Douglas and CES) and restrictions on the number of factors of production (a three-factor capital-land-current inputs model and a two-factor capital-land model). The alternative models of the production of housing services were estimated with the use of household survey data for rental units in two midwestern counties. Housing services of rental units, in contrast to owner-occupied dwellings, are a market good whose quantity can be equated with the market rental payment (with appropriate adjustments for differences in utility payments and other jointly produced services).

Neels estimates the production function directly, using ordinary least squares. He finds that the Cobb-Douglas and translog specifications yield similar elasticities of output with respect to the various factor inputs. However, the two specifications yield different estimates of the elasticity of substitution between factors of production. Estimates derived from the general (four-factor translog) model show high elasticities of substitution between capital and energy (2.14), capital and services (1.27) and services and energy (1.37). Elasticities of substitution involving land are significantly below unity (0.32-0.58).

Quigley (1984) takes an alternative approach toward deriving a model of the demand for household services from a two-factor land-capital housing model. Quigley specifies a two-stage or nested model of housing services production; the production of "real estate" is specified as a function of land and capital, and the production of housing services is specified in turn as a function of real estate and current inputs. The estimable form of the CES production relationships are derived by imposing the optimality condition that the ratio of the relative input prices equals the ratio of marginal products.

Quigley (1984) estimates the production relationships for real estate and housing services from data on the sales of new owner-occupied housing insured under the Federal Housing Administration (FHA) Sec. 203 mortgage program. The data base comprises records of approximately 7000 sales of FHA-insured houses in six California counties in the period 1974-1978. The data base includes the selling price and transaction costs associated with the sale, as well as FHA estimates of the depreciation and operating costs for each house.

Quigley estimates the elasticity of substitution between capital and land at about 0.7; between real estate and operating inputs, 0.3. In contrast, Neels (1981a) estimates the elasticity of substitution between capital and land to be below 0.5, and the elasticity of substitution between capital and operating inputs to be greater than unity. The two studies differ in the types of housing and housing unit tenure studied, the time period of the analysis, and the model specification. It is thus difficult to interpret these differences in the estimated substitution elasticities. The model proposed in the following section is intended to provide additional insight into energy-capital substitution in the production of housing services.

Krumm (1983) develops a model of the demand for residential air conditioning services. The model is based on the relative benefits and costs of alternative systems. The benefits of air conditioning are derived from a Marshallian demand function for air conditioning services, which can be derived from an indirect utility function using Roy's identity:

$$ac_t = f(Pac_t, P, W; X_t) \tag{2.14}$$

where:

ac_t = demand for air conditioning at time t,

Pac_t = price of air conditioning services,

P = vector of prices of other commodities,

W = household wealth, and

X_t = measure of weather at time t.

The costs of residential air conditioning services are associated with a household production function for air conditioning services:

$$ac = g(e, S, H; X) \tag{2.15}$$

where:

e = quantity of energy inputs,

S = vector of air-conditioning system inputs,

H = vector of housing capital inputs, and

X = vector of weather variables.

The production function g is assumed to be linear homogeneous in e, S, and H. The demands for factors of production e and S can be derived from the usual first-order conditions that the relative marginal products of the factors of production be proportional to relative factor prices.

Krumm shows that the assumption of linear homogeneity does not constrain the elasticities of demand for e and S with respect to output ac to be equal for a given housing unit H. This model is thus consistent with the observation that a preference for central air conditioning is positively associated with a relatively high demand for air conditioning services.

The empirical approach chosen by Krumm is to (1) derive an expression for the total benefit of air conditioning from the demand model, (2) derive an expression for air conditioning costs from the household production model, and (3) specify net benefits as the difference between total benefits and costs. Following McFadden (1973), Krumm defines the net benefits for each air conditioning system option (none, single room air conditioner, multiple room air conditioners, central air conditioning):

$$NB = g(CDD, AT, PCPRI, FM, ROOMS, PELEC, AIRHEAT, AGE) \tag{2.16}$$

where:

CDD = cooling degree-days,

AT = average yearly high temperature,

PCPRI = measure of per capita income,

FM = number of family members,

ROOMS = number of rooms in the housing unit,

PELEC = price of 1000 kWh of electricity,

AIRHEAT = dummy for a ducted heating system, and

AGE = age of the housing unit.

He then estimates a logit model of air conditioning system choice. The key results are that the likelihood of choosing a central air conditioning (CAC) system is significantly related to income (high-income households are more likely to choose CAC), weather (warm climates are more likely to choose CAC), house vintage (newer houses are more likely to use CAC), and the presence of heating ducts (heating ducts lower the incremental costs of CAC and thus make that choice more likely).

Krumm demonstrates that an appliance choice model can be jointly derived from the theories of consumer demand and household production. However, the reduced form of the net benefits model that is actually implemented leaves two issues unresolved: (1) it is not possible to recover the underlying production and utility functions from the reduced form equation and (2) the model does not explicitly address the question of capital-energy substitution, that is, shifts over time in factor proportions used in the production of air conditioning.

The model presented in the following section explicitly captures the relationships between the demand for and cost of household services. It thus should be possible to directly model (1) the factor substitution in the production of space heat and (2) the substitution on the demand side between space heat and other commodities.

3 MODEL OF RESIDENTIAL PRODUCTION AND CONSUMPTION OF SPACE HEAT

This section develops a theoretical framework for modeling the residential demand for space heat. Space heat is a nonmarket good that is both produced and consumed within the household. The production and consumption activities, although simultaneous, are conceptually distinct. The production process involves the choice of technology and the derived demands for factors of production. The consumption process involves choice of the final demand for space heat as one element in the household's market basket of consumption goods.

Although household production and consumption activities are conceptually distinct, it must be demonstrated that they can be distinguished empirically. In the absence of data on the final demand for space heat, the household production model is empirically equivalent to the simpler consumer utility models discussed in Sec. 2. The household production models generate factor demand equations given the unobserved level of final output; the consumer utility model generates derived demand equations given the unobserved level of utility. The factor demand equations and derived demand equations generated by the two models are formally identical.

The modeling framework developed in this section presupposes that the level of final demand for space heat is observable (see Sec. 4 for a discussion of the empirical specification of the final demand variable). In this case, the household production model enables us to impose the restrictions of neoclassical production theory (i.e., Cournot aggregation, Engel aggregation, Slutsky symmetry) as well as the adding-up restriction. Thus we can draw upon the extensive literature on the demand for energy in the industrial sector (see Fuss, 1977, and Berndt and Wood, 1975) as well as the literature on residential energy demand. Given an observed level of final demand for space heat, production is represented by a neoclassical production function or its dual cost function; consumption is derived from a direct or indirect utility function.

One objective of the energy demand models discussed in Sec. 2 is to identify long-run versus short-run behavior. In the demand-production framework developed in this section, consumption can be interpreted as short run, and production as essentially long run. On the basis of this distinction, it is possible to define long-run equilibrium conditions for the production and consumption of space heat and to characterize the behavior of households in disequilibrium. The conditions for long-run equilibrium in the residential market for space heat require that the choice of final demand and the choice of production technology be mutually consistent: (1) the actual level of final demand must equal the desired level of demand and (2) the production technology chosen must be that which minimizes the total cost of providing the desired level of space heat.

In contrast, disequilibrium is characterized by the use of a production technology that fails to minimize the cost of space heat. For example, if the household experiences an unanticipated increase in the price of fuel, then the previously determined factor demands no longer minimize the cost of producing space heat. In the short run, the household can respond to the increased marginal cost of heat by using less, that is, by turning down the thermostat. In the long run, it can alter the production technology, substituting capital for energy. The initial impact of rising energy prices is an increase in the marginal cost of heat; one effect of energy conservation is a decrease in this cost. To the extent that consumer demand is price-sensitive, we should expect final demand to drop in response to the initial increase in the price of fuel, but later rise in response to the conservation-induced decrease in the price of heat. The joint demand-production framework represents these short-run and long-run behavioral responses in a natural way. The model of final demand can be interpreted as a model of short-run behavior, conditioned on the long-run production relationship.

Section 3.1 discusses the basic results of neoclassical production theory that are used in this section. Section 3.2 derives a production model for space heat. Section 3.3 presents the model of final demand.

3.1 NEOCLASSICAL PRODUCTION THEORY

The production of household services can be represented as a production problem (see Deaton and Muellbauer, 1980, chapter 10.) The objective of the production model of space heat is to address the following issues: (1) the determination of energy and capital cost shares, (2) capital and energy price elasticities of demand, (3) capital-energy substitution, (4) returns to scale, and (5) change in model parameters over time. This section reviews the basic findings of neoclassical production theory and uses these results to derive expressions for these economic issues.

The production possibilities set is the set of all feasible inputs and outputs. If this set satisfies the usual regularity conditions, then it can be fully represented by its primal production function, or, equivalently, by its dual cost function (see McFadden, 1978, and Appelbaum, 1978, for detailed discussions of duality theory as applied to models of production). The production function can be written as:

$$F(x) \equiv \max_{Q} \; [Q: \quad (X,Q) \in T] \tag{3.1}$$

where:

X = vector of inputs,

Q = vector of outputs, and

T = production possibility set.

The dual cost function can be written as:

$$C(P,Q) \equiv \min_{X} \; [PX: \quad F(X) \geqq Q] \tag{3.2}$$

where:

C = total cost of production, and

P = vector of factor prices.

The production function represents the maximum output that can be achieved for a given vector of inputs; the corresponding cost function represents the minimum cost of producing a given output. The basic finding of duality theory is that, given the usual regularity conditions, the production and cost functions convey the same information. That is, following the notation of Appelbaum (1978), the production and cost functions are "sufficient statistics" for the underlying production possibility set, and, by extension, for each other.

The choice of functional forms for the production and cost functions is dictated, in part, by the objective of the study. For this study, it is important that the functional forms not place *a priori* constraints on demand elasticities, factor substitution, or returns to scale. Fuss, McFadden, and Mundlak (1978) characterize the necessary and sufficient conditions for a functional form to represent the economic properties of the production relationship, without placing *a priori* restrictions on price or substitution elasticities or returns to scale. For the one-output, n-input production model, they identify $(n+1)(n+2)/2$ distinct economic effects relating to the level of output, returns to scale, distributive share, own-price elasticities, and elasticities of substitution. These distinct effects can be represented by a function with at least $(n+1)(n+2)/2$ distinct parameters. Fuss, McFadden, and Mundlak show that this criterion is satisfied by a second-order Taylor's expansion, which can be interpreted as a local approximation to the true production (or cost) function:

$$f^*(x) \approx f(x) \equiv \sum_i \alpha_i h^i(x) \tag{3.3}$$

where:

f^* = true function,

f = approximating functional form,

x = vector of independent variables,

h = known functions of x, and

α = parameters.

The choice of functional form for h generates alternative forms for function f. If h is the log function, f is the translog form; if h is the square root function, f is the generalized Leontief form; if $h(x) = x$, f is the quadratic form. For convenience, the models developed in this section use the translog form. (The translog form has been used in related studies by Berndt and Wood, 1975; Christensen and Greene, 1976; Fuss, 1977; and Neels, 1981a and 1981b.)

The translog of the production function can be written as:

$$Q = \alpha_o + \sum_i \alpha_i X_i + \frac{1}{2} \sum_i \sum_j \alpha_{ij} X_i X_j \tag{3.4}$$

where:

Q = quantity of output, in log form;

X_i = quantity of the i^{th} input, in log form; and

α = parameters.

The translog form of the dual cost function, which is not the dual of the translog production function, can be written as:

$$C = \beta_o + \sum_i \beta_i P_i + \frac{1}{2} \sum_i \sum_j \beta_{ij} P_i P_j + \sum_i \beta_{iq} P_i Q + \beta_q Q + \frac{1}{2} \beta_{qq} Q^2 \qquad (3.5)$$

where:

C = total costs of production, in log form;

P_i = price of factor i, in log form;

Q = quantity of output, in log form; and

β = parameters.

Directly estimating the translog function is difficult. The large number of regressors associated with the translog form may lead to multicolinearity problems and thus increase parameter estimates.

The assumption of cost-minimizing behavior implies that the cost function is linear homogenous in prices. Linear homogeneity in prices implies that the following restrictions hold: (1) adding up $\left(\sum_i \beta_i = 1\right)$, (2) Cournot aggregation $\left(\sum_i \beta_{ij} = \sum_j \beta_{ij} = 0\right)$, (3) Engel aggregation $\left(\sum_i \beta_{iq} = 0\right)$, and (4) Slutsky symmetry $(\beta_{ij} = \beta_{ji})$. (See, for example, Berndt and Wood, 1975.) This assumption of cost-minimizing behavior makes it possible to represent the cost function with factor share equations, which are more conveniently estimated. In contrast, to derive linear-in-parameter factor share equations from the primal production function, we must assume that the production function is linear homogenous in inputs. This constant-returns-to-scale assumption is not required by cost-minimizing behavior (Appelbaum, 1978). The system of equations derived from the primal function thus places additional restrictions on firm behavior. To minimize the *a priori* restrictions placed on firm behavior, the following discussion considers only the dual cost function and factor share equations derived from the dual function.

Berndt and Wood (1975) derive factor share equations from the translog cost function, using the logarithmic form of Shephard's lemma:

$$S_i = \beta_i + \sum_j \beta_{ij} P_{ij} + \beta_{iq} Q \qquad (3.6)$$

where:

S_i = cost share for factor i;

P_j = price of input j, in log form;

Q = quantity of output, in log form; and

β = parameters, following the notation used in the cost function, Eq. 3.5.

Note that the factor shares sum to one. Thus the error terms, summed across factor share equations, equal zero for each observation. To estimate the cost relationship, we must arbitrarily drop one share equation and estimate the remaining n-1 equations. (The parameter estimates for the n^{th} equation are derived analytically from the estimates for the first n-1 equations, given the restrictions imposed by linear homogeneity.)

The n-1 factor equations do not recover all the information in the underlying cost function. In particular, the coefficients β_q and β_{qq}, associated with the terms Q and Q^2, cannot be recovered from the factor share equations. If we assume linear homogeneity in output, these parameters are fixed by assumption (Appelbaum, 1978). Alternatively, these parameters can be estimated by differentiating the translog cost function with respect to Q, the level of output:

$$\partial \ln C/\partial \ln Q = PQ/C = \beta_q + \sum_i \beta_{iq} P_i + \beta_{qq} Q \tag{3.7}$$

where:

PQ = value of output, and

C = cost of inputs.

This equation represents the economies of scale, that is, the value of output relative to the cost of inputs, as a function of the factor prices and the quantity of output.

The parameters of the cost function, or, alternatively, the system consisting of n-1 factor share equations and one economy of scale equation, can be used to derive estimates for price elasticities of demand, Allen-Uzawa partial elasticities of substitution (AES), and output elasticities. The AES associated with the translog cost function can be written as follows (Berndt and Wood, 1975):

$$\sigma_{ii} = (\beta_{ii} + S_i^{\,2} - S_i)/S_i^{\,2} \tag{3.8}$$

$$\sigma_{ij} = (\beta_{ij} + S_i S_j)/S_i S_j \tag{3.9}$$

where:

σ = AES elasticity of substitution,

S = factor cost shares, and

β = parameters as defined in the cost and share equations.

The own-price and cross-price elasticities of demand can be derived from the AES (Berndt and Wood, 1975):

$$E_{ii} = S_i \sigma_{ii} \tag{3.10}$$

$$E_{ij} = S_j \sigma_{ij} \tag{3.11}$$

where:

E_{ii} = own-price elasticity of factor i and

E_{ij} = cross-price elasticity of factor i with respect to the price of factor j.

Christensen and Greene (1976) represent economies of scale (SCE) as the change in output relative to total cost along the cost-minimizing expansion path. Scale economies are defined as:

$$SCE = 1 - \partial \ln C/\partial \ln Q \tag{3.12}$$

The expression $\partial \ln C/\partial \ln Q$, which relates economies of scale to the underlying cost function, is discussed above (see Eq. 3.7). Equation 3.7 can be applied to define SCE in terms of the underlying parameters of the cost function:

$$SCE = 1 - \left(\beta_q + \beta_{qq} Q + \sum_i \beta_{iq} P_i\right) \tag{3.13}$$

where β = parameters as defined in the cost equation and P and Q are in logarithmic form.

In this section, we have (1) reviewed the properties of the primal production function and dual cost function and (2) derived measures of price elasticities of demand, elasticities of substitution, and returns to scale for the translog cost function and for the system of factor share equations derived from the cost function. In the following section, this framework is used to derive a cost model for space heat.

3.2 HOUSEHOLD PRODUCTION MODEL FOR SPACE HEAT

The household production model for space heat developed in this section is derived from the dual cost function and related factor share equations. The dual cost function is used to represent the household's production activities. We assume that the household chooses the minimum cost set of inputs given the desired level of space heat output. The cost model derived in this section has two factors -- capital and energy. The capital input is an aggregate measure of the energy-conserving capital stock, which includes attic insulation, wall insulation, and storm windows. The energy input is a measure of the quantity of fuel used for space heat, adjusted for differences across fuels in the average efficiency of combustion. (Detailed discussion of the sources and definitions of variables used to estimate the cost and factor share equations is found in Sec. 4.) The production activities of the household can be represented by the following cost function:

$$C = C(Pe, Pk, Qsh) \tag{3.14}$$

where:

C = total (energy and capital) cost of space heat. The capital costs reflect the annualized cost of energy conservation;

Pe = price of the fuel (electricity, natural gas, or fuel oil) used for space heat;

Pk = rental price of energy-conserving capital; and

Qsh = quantity of space heat produced.

We specify the cost function in translog form. The translog form of the cost function can be written as:

$$\begin{aligned} C = \alpha_o &+ \sum_i \alpha_i \, P_i + \alpha_q \, Qsh + \frac{1}{2} \sum_i \sum_j \alpha_{ij} \, P_i P_j \\ &+ \sum_i \alpha_{iq} \, P_i \, Qsh + \frac{1}{2} \alpha_{qq} \, Qsh^2 \end{aligned} \tag{3.15}$$

where:

C = total cost of space heat, in log form;

P = factor prices, in log form; and

Qsh = quantity of space heat, in log form.

Alternatively, the two-input cost function can be fully represented by one factor share equation and by the economies-of-scale equation:

$$Se = (Qe \times Pe)/C = \alpha_e + \alpha_{ee} \, Pe + \alpha_{ek} \, Pk + \alpha_{eq} \, Qsh \tag{3.16}$$

$$SCE = (P \times Qsh)/C = \alpha_q + \alpha_{eq} \, Pe + \alpha_{kq} \, Pk + \alpha_{qq} \, Qsh \tag{3.17}$$

where:

Se = energy cost share;

Pe = price of energy, in log form;

Qe = quantity of energy input, in log form;

SCE = value of heat output relative to the cost of inputs; and

P = shadow price of space heat.

This specification of the production model for space heat assumes that the choice of space heating system is optimal and that the tradeoff between fuel and energy-conserving capital is made subject to that optimal capital choice. To the extent that a common set of explanatory variables determine both heating system choice and the fuel-versus-conservation decision, the model developed in this section is misspecified.

This model specification has been chosen for two reasons. First, investments in energy conservation are much more common than investments in new heating systems. An examination of the shifts over time in the shares of fuel and energy-conserving capital is thus likely to reflect adequately the extent of capital-energy substitution. Second, an explicit model of the choice of capital equipment for space heat would require additional data on alternative heating systems. The data base used for the present study does not include information on the cost, size, or efficiency of space heating systems, nor does it include data on the prices of alternative fuels. To address capital-energy substitution in the context of heating system choice, then, unrealistically strong assumptions about the characteristics of alternative space heating systems would be required.

Useful extensions of the model developed in this section would incorporate an additional equation for choice of space heating system. The cost of heat would then be interpreted as the cost of energy and capital contingent on the choice of space heating system. To incorporate a heating system choice equation in this model, additional data or assumptions are required concerning the characteristics of alternative heating systems.

3.3 FINAL DEMAND FOR SPACE HEAT

This section derives a model for the final demand for space heat that is consistent with neoclassical consumer demand theory and the cost models developed in the previous section. The cost models presented in Sec. 3.2 presuppose that the household seeks to minimize the cost of producing the desired level of space heat. The demand model developed in this section represents the allocation of household resources between space heat and a composite commodity representing all other goods as a function of the relative prices of the two commodities.

The structure of neoclassical consumer demand theory parallels the production theory outlined in Sec. 3.1. The producer's problem is to maximize output, given the cost of inputs, or, alternatively, to minimize the cost of factors of production, given the quantity of output. Similarly, the consumer's problem is to maximize utility, given the level of expenditure (e.g., a budget constraint), or, alternatively, to minimize the level of expenditures required to achieve a given level of utility (see Deaton and Muellbauer, 1980, Sec. 2 for a detailed exposition of the primal and dual representations of the consumer demand model).

The fundamental difference between production theory and demand theory is that the producer's maximand, output, is observable, while the consumer's maximand, utility, is not. Thus, in contrast to the production function, the utility function cannot be estimated directly. The utility maximization framework is used, however, to generate a system of commodity demand equations. This system of demand equations can be derived from a direct utility model, which represents consumer utility as a function of the quantities of commodities consumed. Alternatively, it can be derived from the indirect utility function, which represents consumer utility as a function of commodity prices and household income (see Deaton and Muellbauer, 1980; Christensen, Jorgenson, and Lau, 1975). The direct utility model can be written as follows:

$$\max_{X} U = f(X_i, \ldots, X_n) \text{ such that } \sum_i X_i P_i \leq Y \tag{3.18}$$

where:

X_i = quantity consumed of the i^{th} commodity,

P_i = price of the i^{th} commodity, and

Y = household income.

The vector of commodities, X, that solves the direct utility model is a function of commodity prices and household income. The indirect utility function is derived by substituting this vector of commodities into the direct utility model. This indirect utility function can be written as:

$$V = g(P_i/Y, \ldots, P_n/Y) \tag{3.19}$$

where Pi/Y is the price of the i^{th} commodity relative to household income. (The indirect utility function is homogenous of degree zero in prices and income. Thus the relative level of commodity prices, Pi/Y, is sufficient to determine consumer behavior.)

In a manner parallel to the derivation of a system of factor share equations from the translog production and cost models (see Sec. 3.1), we can derive systems of budget share equations from the translog specification of the direct or indirect utility functions (see Christensen, Jorgenson, and Lau, 1975). The translog direct utility specification for the model of consumer demand can be written as follows:

$$U = \alpha_0 + \alpha_i \sum_i Q_i + \frac{1}{2} \sum_i \sum_j \alpha_{ij} Q_i Q_j \tag{3.20}$$

where:

Q_i = quantity of the i^{th} commodity, in log form, and

α = parameters.

Following Christensen, Jorgenson, and Lau (1975), we derive the following budget share equation by imposing the first-order utility-maximization conditions on the direct utility model:

$$S_i = \frac{\alpha_i + \sum_j \alpha_{ij} Q_j}{\sum_k \alpha_k + \sum_j \sum_k \alpha_{jk} Q_j} \tag{3.21}$$

where:

S_i = budget share for commodity i and

α = parameters.

The budget constraint implies that the budget shares sum to one. Therefore, it is possible to derive the n^{th} budget share equation from the parameters of any n-1 equations.

Alternatively, the budget share equation for space heat can be derived from the indirect utility model:

$$V = \beta_0 + \sum_i \beta_i \ (Pi/Y) + \frac{1}{2} \sum_i \sum_j \ (Pi/Y) \ (Pj/Y) \tag{3.22}$$

where:

Pi/Y = price of the i^{th} commodity relative to household income, in log form.

The budget share equation can be derived from the indirect utility model using the logarithmic form of Roy's identity:

$$S_i = \frac{- \partial \ln V / \partial \ln Pi}{\partial \ln V / \partial \ln Y} \tag{3.23}$$

Applying Roy's identity to Eq. 3.22, we obtain:

$$S_i = \frac{\beta_i + \sum_j \beta_{ij} \ (Pj/Y)}{\sum_k \beta_k + \sum_j \sum_k \beta_{jk} \ (Pj/Y)} \tag{3.24}$$

where β = parameters. Again, the budget constraint implies that budget shares sum to one. Thus, the parameters of the n^{th} budget share equation can be derived from any n-1 equations.

The factor share equations derived from the translog cost and production equations discussed in Sec. 3.1 are linear in parameters. As noted above, they are easy to estimate and their relevant economic properties are easy to derive. In marked contrast, the translog specification of the direct and indirect utility models generate the awkward, nonlinear-in-parameters budget share equations shown in Eqs. 3.21 and 3.24.

The objective of this study is to estimate the final demand for space heat and the demand for its factors of production. However, it is not necessary to estimate a complete system of demand equations for all final consumption goods. A system of log-linear demand equations is not consistent with utility-maximizing behavior (specifically, the log-linear demand system violates the adding-up condition). However, the use of the log-linear form to analyze demand for a single commodity does not imply that demands for all other commodities have the same functional form. (See Deaton and Muellbauer, 1980, Sec. 1.2.) Because the budget share represented by space heat is relatively small, the final demand for space heat is specified in log-linear form. This model is convenient to estimate and interpret. This simplified representation of final demand should be sufficient to differentiate final demand from household production for space heat.

4 EMPIRICAL METHODS

This section discusses the specification of the cost and demand models derived in Sec. 3, data sources, and procedures used to derive or calculate variables used in this study.

4.1 COST AND DEMAND FOR SPACE HEAT

This section presents alternative specifications for the models of the cost and demand for space heat. Two alternative specifications are given for the cost model. The first version is a translog model of the cost function; the second, an energy share equation, derived from the cost model using Shephard's lemma. A single log-linear specification of the demand for space heat is presented.

The translog cost model for space heat is specified as:

$$\begin{aligned} C = {} & \alpha_0 + \alpha_1 Pe + \alpha_2 Pk + \alpha_3 Qsh + (1/2)\alpha_4 Pe^2 + (1/2)\alpha_5 Pk^2 \\ & + (1/2)\alpha_6 Qsh^2 + \alpha_7 PePk + \alpha_8 PeQsh + \alpha_9 PkQsh + \alpha_{10} SIZE \\ & + \alpha_{11} HDD + \varepsilon \end{aligned} \tag{4.1}$$

where:

C = total cost of space heat,

Pe and Pk = factor prices for energy and capital,

Qsh = quantity of space heat demanded,

SIZE and HDD = shift parameters introduced to reflect the influence on space heating costs of the size of the housing unit (in square feet of floor area) and the weather (number of heating degree-days), and

ε = additive error term.

All variables are expressed in logarithmic form. (The derivation of variables used in this model is discussed in the sections that follow.) For empirical estimation, we assume that the household minimizes the cost of production imperfectly. Errors in optimization give rise to the additive disturbance term, ε. We also assume that the error terms are identically and independently distributed (i.i.d) normal with mean zero and variance σ^2.

Alternatively, the cost model can be represented by the factor share equation:

$$Se = (Pe \times Qe/C) = \alpha_1 + \alpha_4 Pe + \alpha_7 Pk + \alpha_8 Qsh + \alpha_{12} SIZE + \alpha_{13} HDD + \varepsilon \tag{4.2}$$

where:

Se = energy expenditures as a share of total space heat expenditures.

The factor share equation is derived from the cost equation by logarithmic derivation with respect to the price of energy. Thus the coefficients α_1, α_4, α_7, and α_8 take on the same values in both equations. As in the cost function specification, SIZE and HDD variables are introduced as shift parameters. The error terms are i.i.d normal.

The economies-of-scale equation, Eq. 3.17, defines the value of space heat output relative to the total cost of production factors as a function of factor prices and the quantity of output. However, in the case of a nonmarket good such as space heat, the value of output is not directly observed. (The price of space heat, which is an argument in the final demand Eq. 4.3, is defined as the average cost of space heat; see Sec. 4.6.) The parameters of the economies-of-scale equation thus can be derived only from the cost function itself. Alternatively, cost function and factor share equations can be estimated jointly, with the cross-equation restrictions discussed in Sec. 3.1. This approach, suggested by Appelbaum (1978), is followed in this study.

The demand function represents the final demand for space heat as a function of household income and the price of space heat. This relationship is expressed in log-linear form:

$$Qsh = \beta_0 + \beta_1 Psh + \beta_2 Y + \beta_3 FAMSIZE + \beta_4 HDD + \varepsilon \tag{4.3}$$

where:

Psh = shadow price of space heat,

Y = household income,

FAMSIZE = number of members of the household, and

HDD = heating degree-days.

FAMSIZE and HDD are introduced as shift parameters. All variables are expressed in logarithmic form.

The system of equations developed in this section is truly simultaneous. First, the endogenous variable Qsh appears as an explanatory variable in the cost and factor share equations. Second, the production and consumption activities represented by the separate structural equations in the model are carried out simultaneously within the household. Unobserved attributes of the household or housing unit are likely to affect both activities; this implies that the error terms will be correlated across equations. In the presence of endogenous explanatory variables and cross-equation correlation of errors, ordinary least squares (OLS) estimation is both inconsistent and biased (see Pindyck and Rubinfeld, 1981). Two-stage least squares (2SLS) provides consistent single equation parameter estimates. Pindyck and Rubinfeld (1981) state that 2SLS estimates are biased in the presence of cross-equation correlation of errors. In that case, three-stage least squares (3SLS) methods yield more-efficient parameter estimates.

The 3SLS methods are used in this study to account for both (1) the presence of the endogenous variable Qsh as an explanatory variable in the cost and fuel share equations and (2) the possible correlation of error terms across equations. First, the variable Qsh is regressed by OLS on all the exogenous variables in the models. Second-stage estimates of the coefficients in the cost and fuel show models are obtained by replacing the estimated values for Qsh for the actual values. (The final demand equation is estimated with OLS; no endogenous variables are present as explanatory variables.) In the final stage, generalized least-squares (GLS) estimates are obtained. These third-stage estimates take into account cross-equation correlation. The 3SLS estimates are obtained with the SYSREG procedure for systems of linear equations developed by the SAS Institute (see Allen, 1982).

4.2 DATA SOURCES

The primary data sources used in this study are the public use data files developed from a series of national household surveys of residential energy use sponsored by the U.S. Department of Energy and its predecessor agency, the U.S. Federal Energy Administration. This series includes the "Lifestyles and Household Energy Use" surveys conducted by the Washington Center for Metropolitan Studies in 1973 and 1975 (WCMS) and the Residential Energy Consumption Surveys (RECS), conducted annually beginning in 1978. These surveys were drawn from multistage stratified samples of all households in the United States. The sample sizes range from approximately 1000 for the 1973 WCMS survey to 6000 for the 1980 and 1981 RECS surveys, the most recent surveys that are currently available. The WCMS and RECS surveys provide detailed information on fuel consumption and expenditures; demographic characteristics; and characteristics of the housing unit, heating system, and energy-using appliances. [A detailed review of these data bases is found in Klein et al., 1985. A review of the National Interim Energy Conservation Survey (NIECS), the RECS survey conducted in 1978, is found in Cowing, Dubin, and McFadden, 1982.] The sections that follow describe the methods used to derive from these household surveys and supplemental data sources the variables used to estimate the cost and demand models.

4.3 QUANTITY OF SPACE HEAT

Central to this study is the concept of modeling the demand and cost of space heat, a nonmarket good, rather than the derived demand for energy. The definition of the quantity of space heat consumed is thus of crucial importance. The commodity that the household demands is a heated living space. This commodity could be measured in terms of (1) the desired interior temperature in the housing unit, (2) the desired difference between the inside and outside temperatures, or (3) the floor area of living space that the household would like to heat, times the desired difference between inside and outside temperatures. The first definition, the desired inside temperature, is a plausible indicator of the quantity of heat demanded. It can be equated with the reported thermostat setting (or with a linear combination of the reported daytime and nighttime thermostat settings). However, it has a major drawback. The observed variation across households is relatively small, particularly in the initial survey year of 1973.

The second alternative, the desired difference between the inside and outside temperature, can be derived from the reported thermostat setting (inside temperature) and the measured number of heating degree-days (the average difference between the outside temperature and 65°F, summed over the total heating season). By defining the quantity of space heat in terms of this temperature difference rather than in terms of the absolute inside temperature, the perceived need for the amenity space heat is defined with respect to the level of cold outside. This relative "need" for space heat is a function of both climate and inside temperature; hence the cross-section variation is much greater. The one limitation of this measure is that it is highly (0.8) correlated with the number of heating degree-days. (The number of heating degree-days is introduced as a scale factor in the cost and demand equations, and this high degree of correlation between an endogenous variable and an explanatory variable may give rise to difficulties in estimating the parameters of the model.)

The third definition represents the quantity of space heat demanded in terms of inside temperature, outside temperature, and the area of the living space to be heated. It is possible to argue that this measure reflects the true objective of the household, to heat a given living space to a desired temperature above the outside ambient temperature. A serious drawback, however, is that this measure may tend to confuse the separate effects of weather and housing unit size on consumer behavior. Given the conceptual and measurement advantages and disadvantages of each alternative, this study will use the second definition: the quantity of space heat is the desired difference between the inside and outside temperature, averaged over the heating season.

4.4 QUANTITIES OF FACTORS OF PRODUCTION

A second issue is the definition of the quantity of factors used for the production of space heat. The WCMS and RECS surveys do not provide a direct measure of the energy or capital inputs used in the production of space heat. Section 1.2 describes the derivation of an estimate of the quantity of energy used for space heat from utility-supplied monthly billing data. In this section, we use an algorithm developed by Dubin and McFadden (1983) to derive an aggregate measure of the stock of energy-conserving capital.

The quantity of energy-conserving capital installed in a housing unit can be expressed as the aggregate impact of the capital -- insulation and storm windows -- on the steady-state heat losses through the building shell. Each increment to the stock of energy-conserving capital marginally reduces the total rate of heat loss. The total contribution of energy-conserving capital can be defined as the difference in the steady-state rate of heat loss relative to an uninsulated house.

Dubin and McFadden have constructed a simple model of thermal loads that uses available survey data on housing unit characteristics, such as building size, number of windows, and presence of insulation and storm windows. This approach follows basic engineering principles (see, for example, *ASHRAE Handbook and Product Directory*, 1977 and 1978), with a number of simplifying assumptions that are required given the limited amount of information available. The approach is as follows: (1) estimate the size of each element of the building shell (window area, wall area, ceiling area), (2) estimate the conductive losses through each element of the shell (in Btu/degree day) and infiltration losses, and (3) estimate total steady-state heat losses by summing the estimated conductive and infiltration losses.

To estimate the total steady-state heat losses for a comparable uninsulated building, we use the algorithm developed by Dubin and McFadden, replacing actual insulation levels with zero levels. The quantity of energy-conserving capital is thus defined as the simulated losses through the uninsulated shell less the estimated actual rate of heat loss. Given the approximate nature of the heat loss algorithm and the data used to estimate heat losses, this measure is at best a rough index of the level of energy-conserving capital relative to other housing units in the sample. Nevertheless, this measure has three properties that make it useful for this study. First, by construction, a house with no insulation or storm windows has zero energy-conserving capital. Second, the measure of capital stock is increasing both at the intensive margin (e.g., percentage of windows with storm windows) and the extensive margin (e.g., the total number of windows, given the percentage of windows with storms). Third, the measure of capital stock is weather-independent. A measure of the expected annual energy savings (Btu/year) reflects both the quantity of capital and the weather. In contrast, this measure (Btu/heating degree-days/year) is weather-independent. Thus the weather effect and the capital price effect can be clearly distinguished.

4.5 COST OF SPACE HEAT

The cost of producing space heat is defined as the total cost of the two production factors, energy and capital. The cost of the energy used to produce space heat is derived by proportionally allocating the total costs of the fuel used for space heating among base, space heating, and (for electricity) space cooling loads (see Sec. 1.2). The cost of energy-conserving capital is derived from estimates of the installed costs of storm windows and insulation (Means, 1973 to 1982). The procedure involves the following three steps: (1) use the procedure developed by Dubin and McFadden (1983) to derive the total area of storm windows, insulated attic space, and insulated wall space; (2) calculate the value of the capital stock of energy-conserving equipment by multiplying the estimated areas of storm windows, wall insulation, and attic insulation by the estimated average cost (dollars per square foot, installed) of each category of equipment (see Means, 1973 to 1982); and (3) derive the rental value of capital equipment by multiplying the capital cost by 0.12, the assumed interest rate.

4.6 SHADOW PRICE OF SPACE HEAT

The shadow price of space heat is a measure of the value to the household of an additional increment of space heat. Because space heat is a nonmarket good, its price cannot be directly observed. For this study, average cost of space heat is used as a proxy. This assumption is equivalent to the assumption of constant returns to scale in the production of space heat (see Sec. 3.1).

4.7 FACTOR PRICES

The factor price of energy is defined as the efficiency-adjusted average price of the fuel used for space heating. The combustion efficiencies of heating systems that use the three major residential space-heating fuels (natural gas, fuel oil, and electricity) vary widely. The combustion efficiency for electric resistance heat is close to 1.0. Recent improvements in furnace design allow seasonal combustion efficiencies in excess of 0.9. However, more typical values are 0.63 for natural gas furnaces and 0.76 for fuel oil furnaces (McMahon, 1984). The high seasonal efficiency of fuel oil furnaces relative to natural gas furnaces reflects differences in climate. Fuel oil systems are operated primarily in colder climates, and are thus operated on a more continuous basis during the heating season. This mode of operation is more efficient than the more intermittent use characteristic of heating systems operated in milder climates. The appropriate measure for the factor price of energy should reflect the cost per Btu of the net energy supplied, rather than the average cost of the fuel consumed. Thus the price of energy is defined as:

$$Pe = Ee/Qe \tag{4.4}$$

where:

Pe = efficiency-adjusted price of the fuel used for space heat,

Ee = energy expenditure for space heat, and

Qe = quantity of space heat produced.

The price of energy-conserving capital is defined in terms of measure of steady-state energy savings discussed in Sec. 4.3. The price of capital equals the rental cost of energy-conserving capital divided by the change in the steady-state heat loss associated with the observed level of energy conservation:

$$Pk = Rk/Qk \tag{4.5}$$

where:

Pk = price of energy-conserving capital,

Rk = rental price of capital, and

Qk = installed quantity of energy-conserving capital.

5 EMPIRICAL FINDINGS

This section discusses residential production and consumption of space heat. Our discussion is based on regression results for a system of three equations: (1) cost of space heat (cost), (2) fuel expenditures as a share of total space heating costs (fuel share), and (3) the final demand for space heat (final demand). The objectives of this section are to (1) characterize space heat production and consumption for national samples of households, surveyed in 1973 and 1981; (2) estimate the elasticities of substitution and price elasticities of demand for factors of production; (3) estimate the price and income elasticities of final demand for space heat; and (4) estimate, on the basis of estimated demand and production relationships, short-run and long-run price elasticities of demand for energy.

5.1 DEMAND AND PRODUCTION OF SPACE HEAT: SAMPLE CHARACTERISTICS

This section reviews average values for the dependent and explanatory variables used to model the residential demand and production of space heat (see Table 5.1). The increase over the 1973-1981 period in the cost of factors of production, particularly energy, is reflected in both the demand and production of space heat. On the demand side, the quantity of space heat (the difference between the average inside and outside temperature) is lower. On the supply side, energy expenditures as a share of total cost have decreased. In both cases the differences observed between the two survey years have the expected sign, although the differences are not significant.

A further indication of the changes in space heat production is the shift in the quantity and value of energy-conserving capital. The quantity of capital (see Table 5.2) is expressed in relative terms. That is, the steady-state heat loss through the building shell, compared to the losses through an uninsulated house of the same dimensions is an indicator of the quantity of capital. Table 5.2 indicates that the average house surveyed in 1981 was slightly more energy-efficient than the corresponding house in 1973. The cost of capital reflects the value of installed insulation and double glazing, measured in current dollars. The shift from 1973 to 1981 thus reflects (1) changes in the cost of energy-conserving capital, (2) changes in the installed quantity of capital, and (3) the larger size of houses included in the 1981 sample.

5.2 DEMAND AND PRODUCTION OF SPACE HEAT: ESTIMATION RESULTS

This section reports regression results for the system of three equations derived above. The cost, fuel share, and final demand equations were estimated jointly with 3SLS methods. Restrictions derived from neoclassical production theory (adding-up, Cournot aggregation, Engel aggregation, and symmetry) were imposed within and across equations.

TABLE 5.1 Demand and Production of Space Heat: Mean Values of Dependent and Explanatory Variables

Variable[a]	Survey Year 1973	Survey Year 1981
Sample Size	384	1773
Dependent Variables		
Total cost of space heat ($)	198.82 (169.23)[b]	667.14 (619.77)
Fuel share	0.661 (0.173)	0.575 (0.208)
Quantity of space heat (°F)	16.772 (13.008)	14.895 (10.436)
Explanatory Variables		
Fuel price ($/$10^6$ Btu)	3.360 (1.078)	12.706 (5.096)
Capital price ($/Btu/degree-day)	0.113 (0.032)	0.259 (0.139)
Home area (ft^2)	1,155 (811.3)	1,708 (1,003)
Heating degree-days (65°F base)	4,268 (3,174)	4,755 (3,832)
Price of space heat ($/°F)	11.858 (10.879)	44.791 (45.047)
Household income ($)	11,092 (10,477)	20,476 (22,698)
Family size	2.945 (2.053)	2.654 (1.735)

[a]Variables used in this study are defined in Sec. 4.

[b]Numbers in parentheses are standard errors of the mean.

Table 5.3 shows the 3SLS coefficient estimates for the cost, fuel share, and final demand equations. The t-ratios are, in general, substantially above one, which indicates that the parameter estimates are reasonably precise. The coefficients associated with several terms were not significantly different from zero. This result has no particular significance because the null hypothesis that the translog coefficient estimates are zero is not useful.

The coefficients of the translog cost function are difficult to interpret directly. Following the usual procedures (see, for example, Berndt and Wood, 1975), we can derive Allen-Uzawa partial elasticities of substitution (AES) and own-price and cross-price demand elasticities from the coefficients of the cost function. Table 5.4 presents estimated elasticities derived from the translog cost function and (directly) from the log-linear demand equation. The own-price elasticity of demand for energy is consistent with the elasticity estimates reported in Sec. 2. The own-price elasticity of demand for energy-conserving capital is larger than the demand elasticity for energy, although still less than one. The price elasticity of demand for both factors decreases from 1973 to 1981.

TABLE 5.2 Energy-Conserving Capital Used in the Production of Space Heat

Component	Survey Year 1973	Survey Year 1981
Quantity of Capital Index[a]		
Total	0.584	0.551
Attic	0.391	0.344
Walls	0.525	0.440
Windows	0.641	0.629
Infiltration	0.861	0.842
Cost of Capital ($)		
Total	561.91 (536.02)[b]	2108.33 (3158.33)
Attic Insulation	281.58 (310.78)	1539.05 (2352.87)
Wall Insulation	168.05 (220.23)	739.17 (1289.07)
Double Glazing	115.33 (129.96)	359.76 (387.81)

[a]Losses through shell compared to an uninsulated house.

[b]Numbers in parentheses are standard errors of the mean.

The 1972-73 heating season follows a long period of stability for fuel prices; in contrast, the 1981-82 heating season follows a decade of substantial inflation in energy prices. The factor demand elasticities estimated for 1973 can thus be associated with long-run behavior. In contrast, the elasticities estimated for 1981 may reflect a partial adjustment to changing fuel prices. The relative magnitude of the factor demand elasticities in 1973 and 1981 is consistent with this interpretation.

The coefficients for the final demand equation indicate that the own-price elasticity of demand for space heat is relatively high, about -0.4; the income elasticity of demand is less than 0.10. The elasticities are relatively stable across the two survey years. The final demand for space heat, whether in 1973 or 1981, reflects the short-run behavior of households, given the existing capital stock. The relative stability of the elasticities of final demand over this period suggests that the environment in which households allocate income among space heat and other final consumption goods has been stable over time.

5.3 SHORT-RUN AND LONG-RUN ELASTICITIES OF DEMAND FOR ENERGY

The objective of this study is to characterize the residential production and consumption of space heat. The factor demand elasticities and final demand elasticities discussed in the preceding section can be associated with long-run and short-run

TABLE 5.3 Production and Demand for Space Heat: Regression Results[a]

Regressor	1973		1981	
Cost Model				
Intercept	-3.551	(-2.91)[b]	-1.674	(-5.91)
Pe	0.964	(8.39)	-0.042	(-0.85)
Pk	0.036	(0.31)	1.042	(21.12)
Qsh	-0.374	(-1.33)	-0.208	(-2.24)
Size	0.485	(6.29)	0.505	(24.11)
HDD	0.678	(5.13)	0.700	(29.21)
Pe^2	-0.038	(-1.86)	0.119	(17.94)
Pk^2	-0.038	(-1.86)	0.119	(17.04)
Qsh^2	0.063	(0.82)	-0.021	(-1.14)
PePk	0.038	(1.86)	-0.119	(-17.04)
PeQsh	-0.048	(-3.05)	0.003	(0.35)
PkQsh	0.048	(3.05)	-0.003	(0.35)
Fuel Share Model				
Intercept	0.964	(8.46)	-0.-42	(0.85)
Pe	-0.038	(-1.87)	0.119	(17.07)
Pk	0.038	(1.87)	-0.119	(-17.07)
Qsh	-0.048	(-3.07)	0.003	(0.35)
Size	-0.134	(-11.19)	-0.119	(-15.90)
HDD	0.108	(8.79)	0.121	(17.87)
Final Demand Model				
Intercept	-2.112	(-5.56)	-1.038	(-7.28)
Psh	-0.434	(-15.80)	-0.437	(-41.02)
Income	0.083	(2.98)	0.050	(4.87)
Family Size	0.074	(2.11)	0.016	(1.07)
HDD	0.616	(18.94)	0.581	(45.52)
Weighted R^2 for System	0.533		0.582	

[a]3SLS coefficient estimates for the system of equations.

[b]Numbers in parentheses are t-statistics.

TABLE 5.4 Production and Demand for Space Heat: Estimated Elasticities[a]

Elasticity	1973	1981
Allen Elasticities of Substitution[b]		
σ_{ee}	-0.600 (0.030)	-0.379 (0.012)
σ_{kk}	-2.281 (0.059)	-0.694 (0.016)
σ_{ek}	1.169 (0.042)	0.513 (0.014)
Own-Price Elasticities of Demand[b]		
E_{ee}	-0.397 (0.020)	-0.218 (0.007)
E_{kk}	-0.773 (0.020)	-0.295 (0.007)
Cross-Price Elasticities of Demand[b]		
E_{ek}	0.396 (0.014)	0.218 (0.006)
E_{ke}	0.773 (0.028)	0.295 (0.008)
Price Elasticity of Final Demand	-0.434 (0.027)	-0.437 (0.011)
Income Elasticity of Final Demand	0.083 (0.028)	0.050 (0.010)

[a]Numbers in parentheses are standard errors of the mean. Standard errors for elasticity estimates derived from the cost model are asymptotic. See Kmenta (1971), p. 444.

[b]Calculated at mean value for fuel share.

behavior, respectively. In this section, short-run and long-run price elasticities of demand for energy are derived from factor demand and final demand elasticities in order to compare the results of this study with the literature on residential energy demand.

The short-run elasticity of demand for energy reflects the price-induced change in energy demand associated with a change in the final demand for space heat when the stock of energy-conserving capital is held constant. The long-run elasticity of demand for energy reflects the total change in energy demand, which includes (1) short-run adjustments derived from the shift in final demand and (2) factor substitution, which can be envisioned as a movement along the unit cost curve.

The short-run price elasticity of demand for energy can be written as follows:

$$\frac{\partial \ln Qe}{\partial \ln Pe} = \left(\frac{\partial \ln Qsh}{\partial \ln Psh}\right)\left(\frac{\partial \ln Psh}{\partial \ln Pe}\right)\left(\frac{\partial \ln Qe}{\partial \ln Qsh}\right) \qquad (5.1)$$

where:

$\partial \ln Qsh/\partial \ln Psh$ = own-price elasticity of demand for space heat, given in Table 5.4;

$\partial \ln Psh/\partial \ln Pe$ = relative change in the price of space heat with respect to a change in the price of energy (i.e., fuel expenditures as a share of total expenditures); and

$\partial \ln Qe/\partial \ln Qsh$ = relative change in the demand for energy, associated with a change in the final demand for space heat. By assumption, the change in energy consumption is proportionate to the change in final demand for small changes in Qsh.

On the basis of the above assumptions, we can derive values of the short-run demand elasticity for energy. At mean values for fuel shares, the short-run demand elasticities are -0.287 in 1973 and -0.251 in 1981. These estimates are broadly consistent with short-run demand elasticities cited in the energy demand literature (see Bohi, 1981, Tables 3.1 and 4.1).

The long-run elasticities of demand for space heat reflect the impact of fuel substitution as well as change in final demand. These long-run elasticities can be derived by adding the short-run component derived above and the long-run component derived from the cost function. This derivation is shown in Table 5.5.

TABLE 5.5 Short-Run and Long-Run Elasticities of Demand for Energy

	Survey Year	
Elasticity	1973	1981
Short-Run Component	-0.287	-0.251
Long-Run Component	-0.397	-0.218
Total (long-run) Elasticity of Demand	-0.684	-0.469

This analysis suggests that the short-run demand elasticity for energy used for space heat is in the -0.25 to -0.3 range, and the long-run elasticity is approximately double that value, in the -0.45 to -0.70 range. These estimates are close to those found in earlier studies using similar disaggregate data bases. For example, McFadden, Puig, and Kirshner (1978), using the 1975 WCMS survey, estimate short-run and long-run elasticities of demand for electricity of -0.25 and -0.66, respectively. Hewlett (1977), using pooled survey data from 1973 and 1975, estimates short-run and long-run elasticities of demand for electricity of -0.16 and -0.45 (cited in Bohi, 1981, Table 3.1). Hewlett also reports short-run and long-run elasticities of demand for natural gas of -0.28 and -0.37 (see Bohi, 1981, Table 4.1). The similarity of energy demand elasticities derived here to results in the energy demand literature is indirect evidence for the validity of the underlying model.

6 RESIDENTIAL SPACE HEAT: POLICY ISSUES

In the years since the 1973 oil embargo, many policy researchers have questioned whether changes in energy prices have had a disproportionately adverse effect on poor households. After analyzing 1972-73 pre-oil-embargo data, Newman and Day (1975) concluded that "the poor use less; they pay higher prices for the energy they must have; and, more than any other group of Americans, they suffer from exposure to the noxious by-products of energy consumption and production" (p. 87). The joint model of the production and consumption of space heat developed in this study provides a framework for assessing the policy implications of higher energy prices.

The policy issues raised by this study are (1) the impact on households of recent changes in residential fuel prices, (2) household responses to those changes in relative prices, and (3) government policies or programs to mitigate the impact of higher prices or accelerate the adaptation of households to those price changes. This section shows how the model of joint production and consumption of residential space heat can be used to address policy issues of this nature. Section 6.1 discusses the use of the model for policy simulation. Section 6.2 presents in greater detail the range of policy issues that can be addressed. Section 6.3 presents results for one application of the simulation model. Section 6.4 discusses limitations of this study and suggests directions for future research.

6.1 SIMULATION MODEL OF RESIDENTIAL SPACE HEAT

This section derives a simulation model of space heat from the joint model of production and consumption estimated in Sec. 5.2. The simulation model uses the 3SLS coefficients of the cost, fuel share, and final demand equations to calculate predicted values for the total cost, quantity, and shadow price of space heat and for the factor share of energy. It applies the linear simulation procedure SIMLIN, developed by the SAS Institute, Inc. (see Allen, 1982). First, reduced-form equations for the three endogenous variables are calculated from the 3SLS parameter estimates of the structural equations. The reduced-form equations express total cost of space heat, fuel share, and final demand (Qsh) as functions of the exogenous variables only. The structural cost model is specified as translog; thus, the endogenous variable Qsh appears on the right-hand side both directly and in several second-order terms (PeQsh, PkQsh, Qsh^2). Thus reduced-form equations that are linear in the exogenous variables cannot be calculated.

An iterative procedure is used to make the reduced-form equations linear. First, higher-order terms involving endogenous variables (e.g., Qsh^2, PeQsh) are treated as exogenous. The reduced-form equations now express cost, fuel share, and final demand as a function of all the other variables in the model. These equations are solved for estimates of cost, fuel share, and final demand. An estimate for the price of space heat is calculated by dividing cost by quantity of space heat. The estimated values for the endogenous variables are then used to calculate new values for the second-order terms. For example, the new value for PeQsh is $Pe*Q\hat{s}h$, where $Q\hat{s}h$ is the estimated value for final demand. The reduced-form equations are then solved for second-round estimates of cost, fuel share, and final demand, and a second-round estimate of the price of space heat is calculated. This procedure can be repeated until a consistent set of values for cost, fuel share, final demand, and price of space heat are obtained. In this study, third-round estimates of cost, fuel share, Qsh, and Psh were obtained. Because these third-round estimates differed only slightly from the second-round estimates, the iterations were ended.

6.2 POLICY ISSUES

Policy issues raised by this study fall into three broad classes: the impacts of energy price changes on households, household responses, and government policies or programs. This section reviews each of these policy areas.

The impacts of higher energy prices on households include (1) an increase in the cost of providing energy-using services such as space heat and (2) a shift in the cost-minimizing set of factor inputs associated with the production of such services. The magnitude of these impacts is a function of demographic characteristics of the household and existing attributes of the housing unit and space heating system. Particularly affected have been poor households, households that heat with fuel oil, and residents of housing units that are in a poor state of repair.

The responses available to the household include decreasing final demand and substituting capital for energy in the production of space heat. A decrease in final demand implies that the household lowers the thermostat setting during the heating season. Capital substitution may involve any of the following: (1) routine maintenance of the housing unit or heating system; (2) energy conservation; (3) fuel substitution, that is, switching to a heating system that uses a less costly fuel; (4) replacement of the furnace by a more efficient unit; or (5) the use of supplemental heating sources, including active or passive solar systems and wood stoves.

Policy initiatives available to the government include measures designed to mitigate the impacts of higher energy prices and measures designed to encourage capital-energy substitution. The former include the Low Income Home Energy Assistance Program (LIHEAP), which directly subsidizes the utility bills of poor families and is intended to assure that the poor can afford to heat their homes adequately. (See U.S. Department of Health and Human Services, 1983.) The latter include (1) weatherization programs, in which poor households are given subsidies to insulate their homes; (2) tax credits, which subsidize energy conservation and the use of alternative energy sources; and (3) minimum standards for new buildings and appliances, which set insulation levels for buildings and combustion efficiency standards for furnaces.

6.3 IMPACTS OF ENERGY PRICES ON POOR AND NONPOOR HOUSEHOLDS: AN APPLICATION OF THE SIMULATION MODEL

This section simulates the impact of rising energy prices on three prototypical households. The characteristics of these households are defined by taking the means of exogenous variables for all households in the 1973 sample, for all poor households, and for

TABLE 6.1 Characteristics of Three Prototypical Households: 1973 WCMS Survey

Characteristic	Population Category		
	Total	Poor	Nonpoor
Exogenous Variables			
Price of energy ($1972\$/10^6$ Btu, efficiency adjusted)	3.46	3.79	123.43
Price of capital (1972$/Btu/degree-day)	0.12	0.13	0.12
Housing unit size (ft^2)	1,289	925	1334
Heating degree-days (65°F base)	4,643	4,388	4,674
Household income	12,613	3,010	13,780
Endogenous Variables			
Quantity of space heat (Δ°F)	18.06	15.41	18.38
Shadow price of heat (1972$/Δ°F)	15.23	22.45	14.35
Total cost of space heat (1972$)	219.66	175.85	225.00
Fuel share	0.70	0.86	0.68
Expenditure share	0.017	0.058	0.016

all nonpoor households. Table 6.1 shows the characteristics of the three prototypical households. In 1973, the average poor household, compared to the average nonpoor household, was smaller and lived in a smaller dwelling. The poor household demanded less heat (approximately two-thirds of the 3°F difference in demand reflects a difference in reported thermostat setting; the balance, differences in climate). The poor household also spent less on space heat. However, the average price of fuel faced by poor households is somewhat higher, and the shadow price of space heat markedly so. This finding highlights the comment of Newman and Day (1975) that "the poor pay higher prices for the energy they must have." Factors which may contribute to the higher shadow price for space heat faced by poor households include: (1) the quality of construction and maintenance of the housing unit; (2) the relatively low stock of energy-conserving capital; and (3) the higher marginal energy price associated with a lower level of demand, which reflects the declining-block structure of utility rates.

Table 6.2 shows the simulated response of the three prototypical households to shifts in the real price of energy over the period 1973-1981, holding all other exogenous variables fixed. This simulation illustrates the adverse impact of rising energy prices on

TABLE 6.2 Simulated Response of Prototypical Households to Changes in Real Energy Prices

Variable and Heating Season	Population Category		
	Total	Poor	Nonpoor
Quantity of Space Heat (Δ°F)			
1972-73	17.47	12.80	17.95
1974-75	15.71	11.13	16.22
1978-79	14.09	10.21	14.50
1981-82	11.59	8.18	11.97
Price of Space Heat (1972$/$10^6$ Btu)			
1972-73	12.20	16.86	11.86
1974-75	16.46	25.03	15.79
1978-79	22.37	31.91	21.66
1981-82	38.82	59.57	37.19
Total Cost of Space Heat (1972$)			
1972-73	213.12	215.89	212.96
1974-75	258.59	278.60	256.19
1978-79	315.16	325.82	314.08
1981-82	449.79	487.46	445.24
Fuel Share			
1972-73	0.653	0.707	0.648
1974-75	0.651	0.704	0.646
1978-79	0.648	0.702	0.643
1981-82	0.644	0.697	0.639
Expenditure Share			
1972-73	0.017	0.072	0.015
1974-75	0.021	0.093	0.019
1978-79	0.025	0.108	0.023
1981-82	0.036	0.162	0.032

poor households. The cost of space heat for all households approximately doubles over the 1973-81 period, both in absolute terms and as a share of total expenditures. For poor households, however, space heating costs exceed 15% of total expenditures by the end of the simulation period.

One striking result is the significant shift over time in the final demand for space heat. In contrast, the simulated factor share of energy is stable from 1975 on. This indicates that the adjustment to higher prices has been largely on the demand side. This result may also reflect the difficulty of forecasting the impact of energy prices substantially higher than the range of prices for which the original model was estimated.

A further indication of the impact of energy expenditures on poor households is the relatively high fraction of energy expenditures devoted to space heat. Table 6.3 shows that space-heating energy costs as a share of total residential energy costs have risen steadily over the 1973-81 period. For poor households, nearly 80% of the household energy budget was devoted to space heat in 1981. For nonpoor households, only 60% of the energy budget was spent for space heat, despite the somewhat colder climate and distinctly larger dwelling unit.

6.4 DIRECTIONS FOR FUTURE RESEARCH

This study models the joint production and consumption of residential space heat. Regression results are used to derive short-run and long-run demand elasticities and to simulate the household response to changes in the relative price of energy. In interpreting this study's findings, however, one must consider the limitations imposed by the nature of the model and by the accuracy and detail of the available data.

The model assumes that households make two choices: (1) the level of final demand for space heat and (2) the level of factor inputs in the production process. Under this assumption, the household has control over the output decision. That is, it has a thermostat, and it can make energy-conserving capital investments. This control over final demand and over the production process is true of owner-occupied dwellings. Renters, in general, lack full control over the production process and may lack control over final demand as well. Thus the model developed in this study is directly applicable only to owner-occupied dwellings.

The cost model represents the tradeoff between an aggregate energy input and an aggregate energy-conserving capital input. This representation simplifies the full range of production decisions available to the household. First, the household can choose among a number of conventional fuels -- natural gas, electricity, fuel oil, liquid petroleum gas. Second, many households use supplemental heating fuels, especially electricity and wood. Third, the capital investment decisions include the choice of heating system as well as that of energy-conserving capital goods. A complete production model would reflect this larger number of inputs. (It would also require a much more detailed data base, as will be discussed below.)

The data base used in this study comprises two household surveys, conducted in 1973 and 1981. A number of problems are posed by the nature of the data base. First,

TABLE 6.3 Residential Energy Costs: Space Heat vs. All End Uses

Heating Season and Type of Energy Costs	Population Category Total	Poor	Nonpoor
1972-73			
Space heat ($)[a]	139	153	138
All end uses ($)[b]	352	278	369
Space heat as share of total energy costs	0.39	0.55	0.37
1978-79			
Space heat ($)[a,c]	204	229	202
All end uses ($)[b]	440	326	454
Space heat as share of total energy costs	0.46	0.70	0.44
1981-82			
Space heat ($)[a]	290	340	285
All end uses ($)[b]	493	431	507
Space heat as share of total energy costs	0.59	0.79	0.56

[a]Derived from Table 6.2 (total cost x fuel share). Units are 1972$.

[b]Derived from Table 1.2 (adjusted to 1972$ using implicit GNP price deflator). Units are 1972$.

[c]Average of costs for 1977-78 and 1979-80 heating seasons (see Table 6.2).

many of the data are obtained by querying the householder rather than by measuring directly. This method affects both the kinds of questions asked and the reliability of the information obtained. For example, only limited information is obtained on the characteristics of the dwelling unit, such as the number of rooms, floors, windows, and doors; the square feet of living area; the number of storm windows; the presence of wall insulation. This information, even if accurate, is not detailed enough to estimate the steady-state heating loads of the housing unit. In fact, given the source of these data, the potential exists for substantial measurement error. Thus the estimates of the quantity and price of energy-conserving capital used in this study, which are derived from these data on building characteristics, are at best rough approximations. Moreover, the algorithm used to translate building characteristics into estimates of steady-state heat loss (see Dubin and McFadden, 1983) was calibrated for single-family dwellings only. Thus the variables for quantity and price of energy-conserving capital cannot be consistently estimated for multifamily units.

The household surveys provide energy use and cost data for fuels used. The average fuel price can be derived for the space heating fuel used but not for alternative fuels. For the 1973 survey, one can identify the state of residence for each household and thus match the household to statewide average prices for all fuels. This geographic detail is not available, however, for the 1981 survey. (The lack of such geographic detail makes it impossible to estimate directly the choice of space heating fuel. This data limitation underlies the decision to model the demand for an aggregate energy factor rather than individual fuels.) The lack of geographic detail also makes it impossible to match each household with time-series price data for either the fuel used or alternative fuels. Such time-series price data could be used to estimate final demand and fuel share as a function of past as well as current prices.

Each of these limitations in the model or data base points toward areas of future research. The limited applicability of this study to renter-occupied dwelling units and to multifamily units stems from both the difficulty of modeling the behavior of renters and the lack of information on housing unit characteristics and choices available to apartment-dwellers. The lack of data can be remedied by the use of survey data for renter-occupied units, such as data collected for the Housing Assistance Supply Experiment (see Neels, 1981b). Additional information on the characteristics of renter-occupied housing is available in the Decennial Censuses and Annual Housing Surveys. A more difficult problem is posed by the conflicting interests and differing choice sets of landlords and tenants. Additional work is required to develop models that relate final demand and derived factor demands to the joint decisions of landlords and tenants.

The existing model represents the joint choice of final demand for space heat and derived demand for aggregate energy and capital inputs. Two directions in which this model could be generalized are (1) the choice of primary and supplemental heating fuels and (2) additional capital goods decisions, such as tradeoffs between furnace efficiency and cost, or the choice of supplemental heating systems, such as solar or wood. These extensions of the basic model specify the demand for specific heating systems and individual fuels as a function of the prices of alternative fuels and systems. Information at this level of detail is not available in the existing data base.

The current study used information from two household surveys conducted in 1973 and 1981. The results of this study could be tested further by estimating the model parameters for additional survey years -- the 1975 WCMS survey and the 1978, 1980, and (when available) 1982 RECS surveys. These additional data bases could be used to test the stability of the estimated production and demand relationships.

The WCMS and RECS surveys used in this study, despite their limitations, are the best available source of information on household energy demand. They are not, however, the only source. The annual housing surveys provide more detailed information on housing unit characteristics and, additionally, are a source of longitudinal data (the same panel of housing units has been surveyed at several-year intervals since 1974). The 1972-73 and 1980-81 Consumer Expenditure Surveys provide more detailed information on all housing expenditures (such as mortgage or rent payments, taxes, utilities, and so on).

Future research could explore alternative methods for using information from two or more data sources. Information on housing unit characteristics from the Annual Housing Surveys and on household expenditures from the Consumer Expenditure Surveys are more detailed and possibly more reliable than similar information in the WCMS and RECS surveys. This additional information could function as (1) a source of data for additional simulation studies and (2) a source of *a priori* information on household characteristics and behavior to be used in constraining the cost or demand model.

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